

EFFECT OF AGGREGATE ON THE QUALITY OF CONCRETE

by

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INTRODUCTION

Aggregate, either fine or coarse, is inert filler material added to cement paste to increase its bulk. Aggregate constitutes about 75 per cent of the volume of concrete, as shown in Fig.1 below. Consequently, aggregate characteristics influence, to a large degree, the workability, strength, durability, and economy of concrete.

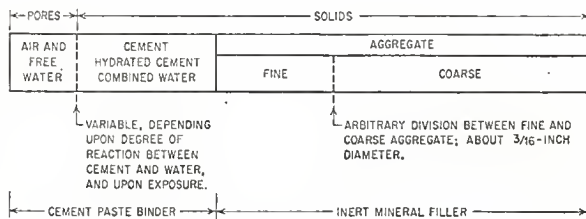


FIG. 1. Composition of concrete.

The aggregate has three principal functions: (1) To provide a relatively cheap filler for the cementing material, (2) to provide a mass of particles which are suitable for resisting the action of applied loads, abrasion, the percolation of moisture, and the action of weather, and (3) to reduce the volume changes resulting from the setting and hardening process, and from moisture change in the cement-water paste.

Aggregates can be grouped in various ways; for example, we can classify them according to their origin into igneous, sedimentary, or Metamorphic, or according to the way in which they are produced into natural sand and gravels, crushed rocks or manufactured aggregates. To

some extent, these classifications overlap; thus the sedimentary rocks include natural sand and gravels, and both of these, and crushed rocks form most of the normal weight aggregates. Manufactured aggregates include all the light-weight aggregates. Aggregates are therefore classified as follows:

1. Petrological classification (Igneous rocks
(Sedimentary rocks
(Metamorphic rocks,
2. Sand and gravel,
3. Manufactured and light-weight aggregates,
4. Heavy aggregates.

Basically, a good aggregate must have certain properties in order to give workable, strong, durable, and economical concrete. Such properties include hardness, soundness, strength, toughness, and resistance to alkali. In addition, aggregates must be properly graded and have the desired weight and the particles must be well shaped, with good surface texture.

It is also important that aggregates do not contain excessive amounts of deleterious substance such as organic impurities, silt or clay, soft fragments, coal or lignite, clay lumps or combustible or volatile materials all of which are harmful in concrete.

Aggregates of different mineral composition may not give the same strength and quality of concrete for a given water-cement ratio because of the differences in strength and densities of the aggregate particles, but the commonly used aggregates such as the natural sand, gravels, crushed stones, and slag give approximately the same results for a given water content. Of interest, however, are the effects of other characteristics of aggregates on the proportion of concrete.

In general, the problem in designing concrete mixtures is the selecting and proportioning of the different size of aggregate particles for the work-

bility with the chosen water-cement ratio.

The important factors affecting workability are:

1. Grading of aggregate.
2. Shape and surface roughness of the paste.
3. Water-cement ratio of the paste.
4. Quality of cement paste.

Maximum strength in both flexure and compression are secured with coarse aggregate of about 3/4-inch maximum size. This was in spite of normal reactions in mixing water which caused water-cement ratio to become less as size of aggregate increased. In spite of the lower mixing water requirement for large maximum sizes, strength may actually be less than for the intermediate or small size.

In 1940, Thomas E. Stanton published results indicating that certain reaction silica constituents present in some aggregate can react with the alkali in cement to cause abnormal expansion and map-cracking in mortar and concretes. The bond between the aggregate and the matrix is affected by chemical reaction at the surface of the aggregate by surface texture and other characteristics of aggregate, which has a significant effect on the strength, permeability and durability of concrete.

In order that a concrete be durable, in so far as the influence of the aggregate is concerned, it is important (1) that the aggregate be resistant to weathering between the aggregate minerals and component of the cement, and (2) that the aggregate contains no impurities which affect the strength and soundness of the cement paste. Either weathering action or chemical reactions is affected by the physical characteristics of the aggregates. Important factors are the porosity and pore size distribution of aggregate and permeability and thickness of the mortar cover protecting the aggregates from water.

The different responses of aggregates to freezing when saturated depends upon the pore characteristics of the aggregates and the cement paste. Saturated aggregates of low porosity may accomodate pore water freezing by simple elastic expansion. Saturated aggregates of moderate or high porosity may fail externally because the particule dimension exceeds a certain critical size or may cause failure in the paste immediately adjacent to the aggregate particles because of aggregate pore water displacement. The magnitude of the hydraulic pressure developed is significantly influenced by the size of the aggregate particle and the permeability and air content of the surrounding paste.

The light-weight aggregate industry is a mere infant compared with the sand, gravel and crushed stone. However, it is growing rapidly, and even now occupies an important position in building construction. The modern light-weight aggregate industry was born in 1917 when Stephen J. Hayel developed a process for expanding shale and clay into sound, hard, light-weight expellets suitable for use as aggregate in structural concrete.

Of course the principle advantage of light-weight concrete is that it reduces the dead load which is carried by concrete sturctures. This reduced weight coupled with high strength has led to growing demand for its use in the structural concrete field.

The U. S. Bureau of Mines estimated that 4,000,000 tons of expanded shale, clay and slate and 30,000,000 tons of expanded slag were produced in 1957.

GENERAL CHARACTERISTICS OF AGGREGATES

Aggregate may be generally classified as to source, mineralogical composition, mode of preparation, and size. With reference to sources, aggregate may be natural or artificial; i.e., the substance of which the particles are composed may be the result of natural processes, or it may have been produced by some industrial process. The natural sand and gravels are the product of weathering and the action of running water, while the "stone sands" and crushed stones are produced from natural rock by crushing and screening of quarried material.

The principal qualifications of aggregate for concrete are that they be clean, hard, tough, strong, durable, and of the proper gradation. Under cleanness comes the requirement of freedom from excess silt, soft or coated grains, mica, harmful alkali and organic matter. Aggregate should be inert to cement and water. Opal and chalcedony are serious offenders, but other siliceous minerals, and even natural and man-made glasses may cause trouble. Destruction is caused by forces resulting from the formation in the concrete which, in company with hydrated cement paste acting as a semi-permeable membrane, creates osmotic pressure tending to burst the concrete. Porous aggregate of large pore size, even though such pores may be inter-connected, is less susceptible to damage by freezing because large pores are less tenacious in their retention of water than are small pores. Tests have been developed for detecting or measuring these undesirable constituents. (1)

Hardness

Hardness of an aggregate means its resistance to surface abrasion. Concrete subjected to abrasive active action in loading platforms, warehouse and pavements should be made with hard aggregate. (2) Weak particles tend

to lower the strength of concrete, although they must present in some appreciable quality before there is a noticeable effect on compressive strength. The effect is more marked upon flexural or tensile strength. Soft particles may be objectionable not only from the standpoint of strength and durability, but especially if the surface of the concrete is to be subjected to wear or abrasion. (3, 4, 5)

The Los Angeles abrasion test is used to determine the quality of coarse aggregate. Wear or loss in the Los Angeles test appears to result from both impact and surface abrasion, the loss in the Los Angeles abrasion test has correlated with the strength of concrete prepared with variety of aggregate. (6)

Soundness

Soundness of an aggregate is its ability to withstand repeated cycles of freezing and thawing, and other types of weathering. It is important the sound aggregates be used in exposed concrete. (2)

Volume changes in unsound aggregate particles may result in deterioration of concrete, ranging from localized pitting and scalling to extensive cracking and deep-seated disintegration. The former is usually of little structural significance but may be detrimental to the appearance of the structure, the latter may be sufficient to cause structural failure of the concrete. (3)

Unsound aggregate particles fall into two general categories, depending upon the nature of their changes in volume. In the case of one class of particles, the soft sandstones, others, clay lumps, etc. disintegration of concrete results from failure of the aggregate particles to maintain their integrity breaking into numerous smaller pieces. Depending upon the quality of sand particles, deterioration may be general or more often, may be evidenced primarily by surface pitting or seating. (31)

A second and more dangerous class of unsound particles consists of those which expand disruptively in the concrete. Examples of this type are certain laminar rocks - principally limestone containing expansive clays - and porous chert. Such materials, when frozen in saturated condition or, in some cases, when merely exposed to water, increase in volume with the development of sufficient pressure to cause deep-seating disintegration of the concrete.

The overall soundness of an aggregate is most often specified in terms of a maximum permissible loss in the sulfate soundness test. That list consists of alternate immersion of a carefully graded and weighed test sample in a solution of sodium or magnesium sulfate, and oven drying under specified conditions. The enlargement of salt crystals in the pores of the aggregate tends, presumably, simulating the action of freezing water. Loss is measured after a specified number of cycles. Usually either 5 or 10 in terms of the amount of the sample that will pass the sieve upon which it was originally retained. (7)

One method which has received considerable attention is the uncombined freezing and thawing test. It resembles the sulfate test except that, instead of being alternately immersed in salt solution and oven-dried, the sample is alternately frozen and thawed, usually while immersed in water. The method is more time-consuming than sulfate test, and it provides no more, and possibly less, information. It has not received wide acceptance. (7)

Strength

Strength of an aggregate is its resistance to high compressive forces. (2)

Toughness

Toughness of an aggregate is its resistance to impact. It is necessary in

concrete used in loading platforms, pavements and other structures subjected to direct impact. (2, 7)

Chemical Reaction

Chemical soundness of an aggregate means that it will not react chemically with cement. In some areas, aggregates with certain chemical constituents react with alkalis in cement, and may cause deterioration of the concrete. This chemical action is known as alkali-aggregate reaction. (2)

The formation of the products of the reaction between the alkalis and the aggregate cause abnormal expansions. (3)

Gradation

Gradation of an aggregate refers to particle size distribution and is usually determined by a sieve analysis. Sieve size commonly used for grading coarse aggregates are $1\frac{1}{2}$, $3/4$, $3/8$ inches, No. 4; for fine aggregates sieves numbered 4, 8, 16, 30, 50, and 100 are used. Numbers refer to the number of square openings per inch.

Unit Weight

Weight of unit volume of coarse aggregate is relatively constant whereas that is variable, depending upon; its moisture content, a phenomenon known as bleeding. If aggregates are proportioned by volume, weights should be measured periodically, and the concrete mix design adjusted accordingly. (2)

In estimating quantity of materials, and in mix computations when batching is done on a volumetric basis it is necessary to know the conditions under which the aggregate - volume is to be measured: (1) loose or compact, and (2) dry, damp or inundated. For scheduling volumetric batch quantities, the unit

weight in the loose, damp state should be known. The unit for any given conditions may be determined by weighing the aggregates required to fill an appropriate container of known volume. (3)

Particle Shape

Particle shape is important in both coarse and fine aggregate; flat and elongated pieces will make a concrete mix harsh and may weaken concrete members subject to flexure. Aggregates with high percentages of flat and elongated pieces required high cement factors to produce workable and durable concrete, and some specifications require that such aggregates be rejected. The most desirable shape is spherical or roughly, cubical. (2)

Appreciable number of flat pieces tend to affect durability if the oriented are in such a way as to cause accumulations of water and laitance underneath their bottom surface. Apparently, about 10 or 15 per cent of such shaped particles can be tolerated in an aggregate, but current specifications do not cover, or do not place quantitative limits on, inclusions of this sort. (3)

Surface Texture

Surface texture of an aggregate affects both workability of fresh concrete and bond between the cement paste and aggregate in hardened concrete. Flexural strength and, to a lesser degree, compressive strength are also affected by the texture of aggregate surfaces. (2, 1)

Organic Impurities

Organic impurities may delay setting and hardening of the concrete and may cause deterioration. For example, a very small percentage of sugar in a

concrete mix may actually prevent the setting of cement. Other impurities, although not so disastrous, are harmful in varying degrees and must be guarded against. (2, 7)

Silt or clay in excessive amounts require additional cement paste to coat the greater surface area of the extremely fine particles. Excessive fines tend to rise to the surface while concrete is being finished, resulting in an inferior surface. Even thin coatings of silt and clay on gravel particles are particularly harmful, because they weaken the bond between cement and aggregate particles. (2, 3)

Coal lignite, combustible are volatile materials in excessive amounts affect durability because particles of these impurities at or near the surface may disintegrate or even "pop out". (2, 7)

Other influence and the thermal conductivity of aggregate. These determine to a great degree the temperature gradient within a concrete mass having temperature differences on opposite faces of a section. Where the gradient is sufficiently abrupt the concrete may be subjected to destructive internal strains. (2)

General Classification of Properties

In general, classification of properties is that used by the Bureau of Reclamation to catalogue the physical and chemical condition of particles constituting terms as follows: satisfactory, fair and poor. Chemical stability in concrete is designated by two terms: innocuous and deleterious as follows:

(1) Satisfactory -- particles are hard to firm, relatively free from fractures, and not flat or chiplike; capillary absorption is very small or absent, and the surface of texture is relatively rough.

(2) Fair -- particles exhibit one or two of the following qualities: firm to friable; moderately fractured; capillary absorption small to moderate; flat or chiplike; surface relatively smooth and impermeable; very low compressibility; coefficient of thermal expansion approaching zero or being negative in one or more directions.

(3) Poor -- particles exhibit one or more of the following qualities: friable to pulverulent; slake when wetted and dried; highly fractured capillary absorption moderate to high; marked volume change with wetting and drying; combine three or more qualities indicated under "fair".

Innocuous. -- Particles contain no constituents of which will dissolve or react chemically to a significant extent with constituents of the atmosphere, water, or hydrating portland cements while enclosed in concrete or mortar under ordinary conditions.

Deleterious. -- Particles contain one or more constituents in significant proportion which are known to react chemically under conditions ordinarily prevailing in portland cement, concrete or mortar in such a manner as to produce significant volume change, interfere with the normal course of hydration of portland cement, or supply substances which might produce harmful effects upon mortar or concrete. (8)

EFFECT OF AGGREGATE ON WORKABILITY OF CONCRETE

It is desirable that fresh concrete be relatively easy to mix, transport, deposit, compact, and finish, and that it remain free from segregation during these operations. The composite quality sought, involving ease of placement and resistance to segregation, may be termed "workability".

Knowledge of the workability is most necessary in the production of a "well-designed" concrete mix. There are too many variables which affect

Table 1. Quality of Aggregates

Property	Description	Impairment	ASTM Designation	What to Specify
Hardness	Resistance to abrasion	Warehouse floors, loading platforms, pavements	D2 (rock) D289 (fine gravel) C131 (rock or gravel)	Max. per cent loss
Strength	Resistance to load	Strong concrete	C87 (sand)	Min. per cent of standard mortar strength
Toughness	Resistance to impact	Floors, pavements	D3	Min. drop of hammer to fracture specimen
Soundness	Resistance to freezing and thawing and other types of weathering	Structures subjected to weathering	C88	Max. per cent loss
Gradation	Particle size distribution	Workability of fresh concrete Reduction in voids	C136	Max. size limits of per cent passing sieves
Surface texture	Smooth or rough particle surface	Workability of fresh concrete		
Particle shape		Workability of fresh concrete		
Unit weight	Weight per cu. ft. of aggregate	(a) Slag aggregates (b) Lightweight aggregates	(a) C29	Max. per cent flat and elongated pieces (a) Min. unit weight (b) Max. unit weight
Alkali-resistance	Resistance to chemical reaction with alkalis in cement	All structures	C227	Aggregates must be non-alkali reactive

Table 2. Deleterious Substances in Aggregates

Deleterious Substance	Effect on Concrete	ASTM Designation
Organic impurities	Affects setting, hardening, and might cause deterioration.	C40
Soft fragments	Affects strength and durability.	C235
Coal and lignite	Affects durability.	C123
Silt and clay	Affects durability, may segregate in fresh concrete.	C117
Combustible and volatile material	Affects durability.	
Clay lumps	Affects workability and durability.	C142

workability for it to be the maximum size of the aggregate, the capacity of the aggregates to absorb water, shape and surface characteristic of aggregate particles, grading of aggregate, plasticity of the paste itself, and relative quantities of paste and aggregates. A change in one property of an aggregate affects the other properties, so that a change of grading will affect the bulk density, the ratio of coarse to fine aggregate, and the water absorption. (3, 1)

Different Types of Aggregate

Different types of aggregate produce different degrees of workability. The most workable concrete is produced by using smooth rounded aggregate, particularly water-worn gravels. The workability is reduced when flaky or elongated particles or crushed rock aggregate. (1)

Particle Shape

Particle shape is important in both coarse and fine aggregate. Flat and elongated pieces will make a concrete mix harsh, and may weaken concrete members subject to flexure. Aggregates with high cement factors to produce

workable and durable concrete, and some specific cautions required that such aggregates be rejected. The most desirable shape is spherical or roughly cubical. (2, 9)

The particle shape affects the density of packing. This may be shown by carrying out a bulk-density test on aggregates which differ only by their being round or angular. There is a direct relation between angularity and workability, but the effect of angularity reduces workability. (1)

The shape and plasticity characteristics of the particles affect the plasticity of the mix through their effect on the amount of paste required, and on the friction between the particles as the concrete is molded. Angular particles or those with rough surfaces required a great amount of paste for the same mobility of mass than is necessary for well-rounded particles, or those with smooth and slippery faces, other conditions remaining the same.

Sand with poorly shaped grains usually has a high percentage of voids, and when used as concrete aggregate, it not only results in poor workability but also may cause excessive bleeding, or water gain, in the concrete. (9)

The Absorptive Capacity

The absorptive capacity of an aggregate also with high absorption will tend to reduce the available water in the mix, but this factor is only of secondary importance in most site work. (3)

The Surface Texture

The surface texture of aggregate has an effect on both the workability and strength of the concrete.

Aggregate Grading

During processing at the pit or quarry, aggregates are screened into various sizes. The amount present of material of different sizes is expressed as the cumulative percentage of material passing the various sieve sizes, starting with largest and finishing with the smallest. This cumulative percentage is plotted as a curve. The grading of aggregate is a major factor in determining the workability, segregation, bleeding, handling, placing and finishing characteristics of concrete.

Satisfactory concrete can be made with various gradings of aggregates and there is no limit, however, within which a grading must lie to produce a satisfactory concrete, but this depends upon the shape, surface texture and type of aggregate, and the amount of flaky or elongated material. Variations in the grading of sand can be the cause of wide variations in workability, strength, and other properties, but the grading of the coarse aggregate has less effect.

Attempts have been made from time to time to produce an ideal grading based on the idea that if maximum of solid particles were packed into a concrete mix, then highest density and strength would result. However, such concretes give harsh, unworkable mixes and a certain excess of cement, sand and water is necessary over and above the theoretical amount required. (1)

The effect of the grading is not constant, but depends upon cement and water content. The grading is of little importance in rich mixes, but becomes more important when lean mixes of high workability are required. It is of less importance with round aggregates, and is important for crushed rock aggregates. (1)

Aggregates with very different over-all grading can and often are used to produce concrete of all types with various workability and aggregate cement ratio for such concretes depend directly upon previous experience or upon the carrying out of a number of trial mixes with the proposed aggregates, but the following points may be of help:

If the grading is finer than the type gradings, the mix is probably over-sanded and may be too sticky so that it will hang up the mixer and skips. If the grading is coarser than the type gradings, it may be harsh to compact without causing segregation. A mix containing single-sized large aggregate but with a sand grading close to one of the type gradings will be subject to segregation. (1)

The grading of the aggregate affects the plasticity of the concrete,

(a) by affecting the quantity of paste necessary to fill the spaces thoroughly, and surround the aggregate particles completely, and

(b) by affecting the resistance which is offered to the mobility of the mass through the varying combinations of sizes. (3)

A suitable gradation of the combined aggregate in a concrete mix is desirable in order to secure workability and economy in the use of cement. For mixes of given consistency and cement content, a well-graded mixture produces a stronger concrete than a harsh or poorly graded one, since less water is required to give suitable workability.

Most attempts to secure optimum gradings have been directed toward attaining a combination of materials to produce maximum density consistent with good workability of concrete, and minimum cement requirement for concrete of a given consistency. Three general means may be employed to approach this result: (1) Calculated combinations based upon filling the voids in the

aggregate with successively smaller sizes of materials; (2) combinations calculated from sieve analysis, and (3) trial combinations. (2)

A test for maximum density of combined aggregates is easily made by weight, several proportions of dry rodded mix containing say 0, 30, 40, 50, and 100 per cent, of sand plotting a curve, and observing the percentage of sand at which the unit weight is maximum. For example, in Fig. 2 the maximum weight of mixed aggregate occurs when 38 per cent of sand is used; the optimum percentage of sand is then to be $38 - 3 = 35$. (3)

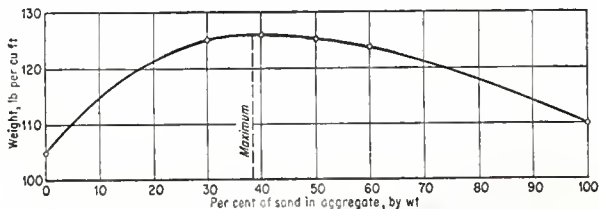


FIG. 2 Unit weight of dry-rodded fine and coarse aggregates mixed in various proportions. (For illustration only, to show trends; values will differ with aggregates.)

Proportion of Fine to Coarse Aggregate

For any given degree of workability, the proper proportion of sand varies with the water content of the paste. For any fine and coarse aggregate used in combination with a given cement paste, there is a definite percentage (called optimum) of sand which, for a given degree of workability, will require the least paste. Smaller or greater percentages than the optimum will require more paste, as indicated in Fig. 3 where the relationship of the paste content to percent of sand is shown. This curve for concrete of medium consistency, similar curves would be secured with other consistencies and other

GRADING

Proportion of Fine to Coarse Aggregate

For any given degree of workability, the proper proportion of sand varies with the water content

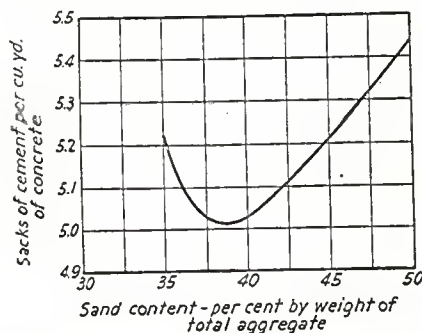


Fig. 3 Effect of sand content on paste requirement. Medium consistency. 6.37 gal. water per sack of cement. Sand graded 0—No. 4 sieve. Gravel graded No. 4— $1\frac{1}{2}$ -in.

aggregate gradings. Points on the curve to the left of the optimum represent mixes that would be too harsh unless additional cement paste was used. Points to the right of the optimum represent mixes that would be too stiff, due to increase of sand, and again, additional paste is required to maintain the workability.

It is sometimes stated that the best proportion of fine and coarse aggregates is that which gives the maximum density of mixed aggregate. This is not necessarily true, as shown in Fig. 4, which gives the relationship between the percentage of sand and water-cement ratio of the paste, and the workability of the concrete mixture. The gradings of sand and coarse aggregate were the same in all of these tests; the maximum size of coarse aggregate being $1\frac{1}{2}$ inches. The curves, each representing a different degree of workability, indicated the proportions of sand which required the least quantity of cement paste. The cross-hatched area represents the proportion of sand

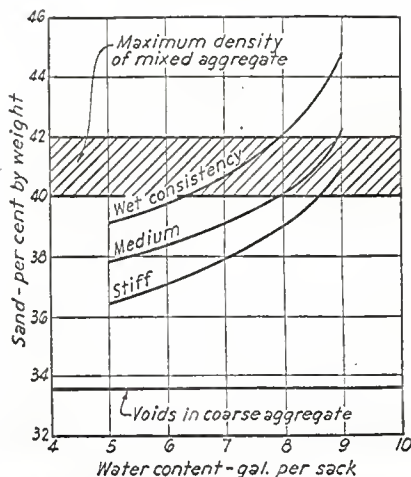


Fig. 4. Relation of sand requirement to water content of paste for concrete mixtures having different degrees of workability.

which gave the maximum density of mixed aggregate. It will be noted that the optimum percentage of sand departs considerably from this percentage for mixtures of low water-cement ratio, and for the stiffer consistencies. (2)

Proportional Aggregate. The proper proportions of fine and coarse aggregate are also affected by the grading of each aggregate. Table 1 gives results of tests in which the same grading of sand was used, but the grading of the coarse aggregate varied, the maximum size being $1\frac{1}{2}$ inches in each case. A constant water-cement ratio and degree of workability were used. Note that with an arbitrary percentage of sand, the cement requirement changes considerably, showing a variation of 1.3 sacks per cu. yd. of concrete, and in all cases, a higher cement requirement than when the optimum percentage of sand was used.

TABLE 3—EFFECT OF GRADATION OF COARSE AGGREGATE
ON CEMENT REQUIREMENT

Water content 6.3 gal. per sack of cement Remolding effort 30					
Composition of Coarse Aggregate— Per Cent by Weight			Optimum* Amount of Sand	Cement Required at Per Cent Sand Indicated Sacks per Cu. Yd.	
4 to $\frac{3}{8}$ -in.	$\frac{3}{8}$ to $\frac{1}{2}$ -in.	$\frac{1}{2}$ to 1 $\frac{1}{2}$ -in.	Per Cent	Optimum	35%
35.0	00.0	65.0	40	5.4	5.7
30.0	17.5	52.5	41	5.4	5.8
25.0	30.0	45.0	41	5.4	6.2
20.0	48.0	32.0	41	5.4	6.0
00.0	40.0	60.0	46	5.4	7.0

*Amount giving best workability with the aggregates used.

If a constant cement factor is used, the optimum amount of sand as described above will produce a mixture requiring the least quantity of water for a given consistency, and therefore will produce the best concrete. (1)

The grading of the fine aggregate also influences the desirable proportions. Fig. 5 shows the effect of grading of fine aggregates on cement requirement of concretes of similar strength and workability. The three different sands shown were combined with coarse aggregate of the same gradation. It will be seen that for a given percentage of sand there is a considerable difference in cement concrete. For example, at 45 per cent sand, the cement content varied from 4.6 to 5.4 sacks per optimum amount of sand was used, as represented by the lowest point of each curve there was little difference in cement content.

There are many theories on the best grading for aggregates to produce maximum workability and economy, and "ideal" grading would vary somewhat with the type of aggregate, with the degree of workability desired, with the

amount of cement in the mixture. While it may be possible to produce one or more ideal gradings for the specific conditions of a given job, this would be practicable only on large jobs, and even then it may not be economical. Practical considerations is the production of aggregates unusually limited selection to a few materials which have been produced to meet the requirements of most concrete work. There are, however, certain fundamentals which should be understood. (2, 10)

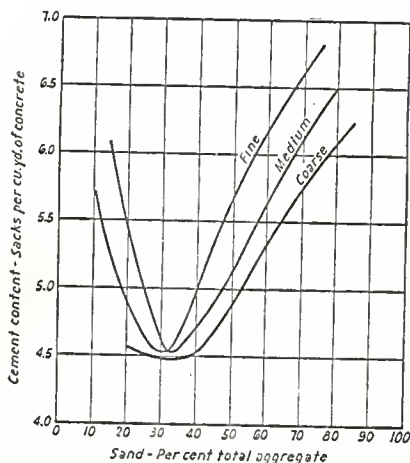


Fig. 5 Relation between sand content and cement required to produce concretes of similar workability testing 2500 lb. per sq. in. at 28 days. Data from R. B. Young, Testing Engineer, Hydro Electric Power Commission of Ontario.

A suitable gradation of the combined aggregate in concrete mix is desirable in order to secure workability and secure economy in the use of

cement. A well-graded mixture produces a stronger concrete than harsh or poorly graded mixtures.

Most attempts to produce maximum density consistent with good workability of concrete, and minimum cement required for concrete of a given consistency.

When the size of aggregate is increased, the weight per cubic foot is increased, and the cement required will decrease. Water required is also decreased.

Some variation in the gradation of aggregate does not seriously affect the quality of concrete. (2,10)

Grading of Fine Aggregate. As seen from Fig.4, there is little difference in cement required in concrete whether fine sand or coarse sand is used, provided the optimum amount of sand is used in each case. In general, the percentage of sand should be less when it is fine than when it is coarse. There are certain objections, however, to using very fine sand such as plaster, sand or beach sand. Combined with coarse aggregate, it often produces a mixture in which it is difficult to avoid segregation. There is also a tendency for too much mortar to come to the surface. The finer the sand, the more likely it is made up predominantly of one or two sizes. It is therefore, generally accepted that coarsely graded sands are most desirable.

On the other hand, all sands must contain a sufficient quantity of fine particles to assist the cement in producing good workability. Specifications usually permit a rather wide range in the quantity of material passing the 50-mesh sieve, the requirements of the American Society for Testing Materials, for example, being 10 to 30 per cent with a provision that on approval of the engineer, this may be 5 to 30 per cent for concrete containing five or more sacks of cement per cubic yard. These lower limits may be sufficient in the

richer mixes under easy placing conditions and with mechanical finishing as for pavements. They are not sufficient in the usual mixes used in wall construction, where 15 to 20 per cent gives better results, even though more than five sacks of cement per cubic yard as concrete is used. (2, 9)

A grading of sand in which one or two particle sizes greatly predominate should be avoided; such a sand has a large amount of cement-water paste to produce a workable mixture. In Fig. 6 points have been plotted to indicate the limits permitted by the Standard Specifications for Concrete Aggregates, Designation C33-49, of the American Society for Testing Materials. Straight lines have been drawn through these points. Curves representing sieve analyses for both fine and coarse aggregate should be between these lines. (2)

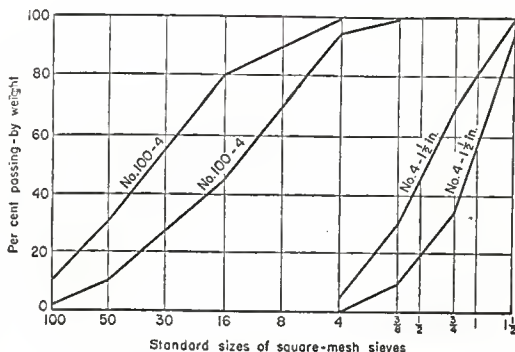


Fig. 6 Limits specified in "Standard Specifications for Concrete Aggregate" (ASTM C33) for fine aggregate (left) and coarse aggregate (right).

Experience has shown that usually for very coarse sand or very fine sand is unsatisfactory for concrete mixtures. The coarse sand results in hardness, bleeding, and segregation. And the fine sand required a

comparatively large amount of water to produce the necessary fluidity also tends to cause segregation. (11)

The presence of organic, prevent the concrete from hardening satisfactorily. Concrete containing organic matter may remain soft and friable for months, and never attain full strength or resistance to abrasion.

Sand for most used is more than 30 per cent passing through a 50-mesh sieve, and not less than 85 per cent passing through a No. 4 sieve.

Grading of Coarse Aggregate. As indicated in Table 1 the grading of coarse aggregate may vary appreciably without affecting the cement requirement for a given water-cement ratio, and workability provided the optimum proportion of sand is used for each grading. This is true for a given maximum size. By increasing the maximum size as to extent, the range over which the particles are graded, the total amount of aggregate that can be used with a given cement paste may be increased, Fig. 7, based on laboratory and field data, illustrates the "influence of size of aggregate on the cement content of concrete of a given slump and quality paste." It will be noted that there is a marked economy in cement as the maximum size is increased up to about three inches. Beyond this point, careful studies would be necessary to determine whether the cost of obtaining and handling larger sizes would offset the saving in cement.

The effect of the maximum size of the aggregate on the efficiency of cement can be measured also in terms of the amount of water required with a fixed amount of cement to produce concrete of a given slump and the effect this has on the strength. (2)

In Fig. 8 a cement content of 5 sacks per cu. yd. of concrete and a slump of 3 to 5 in. are maintained.

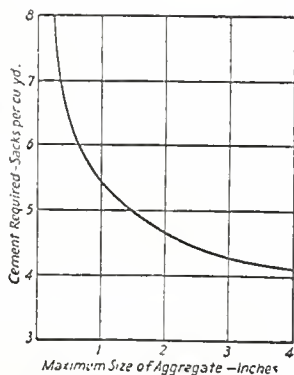


Fig. 7 Effect of maximum size of aggregate on cement requirement for concrete of 3 to 5-in. slump and $6\frac{1}{2}$ gal. mixing water per sack of cement.

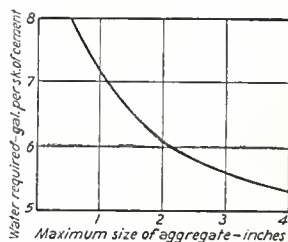


Fig. 8 Effect of maximum size of aggregate on water requirement for concrete of 3-to 5-in. slump with 5 sacks of cement per cu.yd. of concrete.

It will be seen that the amount of water to give this decreases' the maximum size of aggregate increases. This decrease in water requirement increases the compressive strength as indicated in Fig. 9, and also improves the other desirable qualities of the concrete.

The maximum size of aggregate that can be used, of course, is limited by the dimensions of the concrete member and by other considerations. In general, the maximum size should be not more than one-fifth the narrowest dimension of the concrete member nor more than three-fourths the minimum clear spacing between reinforcing bars. Where aggregates larger than $1\frac{1}{2}$ inches are used, the coarse materials should be divided into two or more sizes, measuring and recombining them for each batch. On work where appearance is important, such

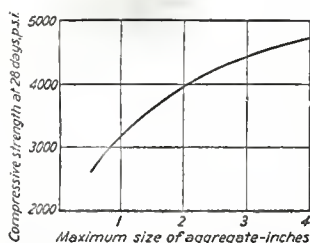


Fig. 9 Effect of maximum size of aggregate on compressive strength of concrete with 5 sacks of cement per cu.yd. of concrete and variable water content to give 3-to 5-in. slump.

as the exterior walls of buildings, where $1\frac{1}{2}$ inch aggregate is often used, it is advisable to secure the coarse material in No. 4 - $3/4$ inch, and $3/4$ - $1/2$ inch sizes and then combine them for each batch in proportions. By doing this, better control of concrete can be obtained.

The grading of coarse aggregate also has definite effect on the workability of the resulting concrete, free from an excessive amount of any one size fraction. Coarse aggregate which have been found very satisfactory so-called "gap gradings or gradings in which one or more of the intermediate size fractions is largely eliminated have sometimes been recommended as desirable, although their advantage having a gap grading is not usually practical in commercial processing plants and the use of such grading is not common.

It may, however, be desirable to have a slight gap in the gradation between fine and coarse aggregate, since this may promote workability in the concrete. As in the case fine and coarse aggregate there should not be an excessive amount of material between any two consecutive sieves in the combined

aggregates as used in the concrete. An excessive amount in $3/4$ into No. 4 sieve size might result if the coarse aggregate contains to pass the $3/8$ inch sieve, and were combined with sand having the maximum permitted to be retained on the No. 4 sieve, such condition as this would tend to produce an excessive amount of $3/8$ inch to No. 4 size in the mixture, causing particle interference that would result in poor workability. (9)

Effect of Aggregate on Water-Cement Ratio

For any one value of the water-cement ratio, there is one ratio of sand to coarse aggregate that produces the greatest workability, but this can often be determined only by experiment. For continuous gradings, the proportion of sand may be 30 to 35 per cent; for gap-graded concrete, the proportion may be 28 to 30 per cent. (1)

For any given paste, that is, a quantity of cement with its definite proportion of water, decreasing the amount of paste with respect to the quality of aggregate stiffens the mixture, and increasing the amount of paste renders the mix more fluid. If the quantity of paste is reduced to the point where there is not enough to fill the spaces and actually float the aggregates, the mix will become granular or harsh, and will be impossible of proper placement. (3, 11)

Air Entrainment

Air-entrainment obtained by the use of air-entrainment cement, or an air-entraining admixture. Air-entrainment alters the properties of both plastic and hardened concrete due to the incorporation of minute air bubbles in the cement paste. It tends to prevent segregation during the handling, thus promoting uniformity and durability.

The benefits in workability derived from air-entrainment are much more pronounced in the leaner mixes, or in mixes with a tendency to be harsh and unworkable. There has been, in some localized areas, objection to the use of air-entrained concrete for floors that are to be finished by means of steel trowels to a very dense smooth surface. This objection has been directed to the actual troweling operation and not to the workability of the concrete as the terms is usually applied. (9)

Admixture Affects on Concrete

Some admixtures have beneficial effect tending to offset the ill effects of increases in water-cement ratio which their use may bring about. An admixture may be beneficial in one or more of the following ways:

1. It may improve the texture of the concrete, a physical effect.
2. It may have cementitious properties of its own.
3. It may be pozzolanic.

When cement paste is of watery character, the heavier particles of cement tend to settle away from under surface of aggregate, leaving water and finest cement particles in immediate contact. This is shown by fact that when concrete made from wet mixtures is broken, aggregates adhere to the upper (as placed) fragment, leaving cavities in the lower section. The full value of cement is not then secured. If cement paste is stiffened, the paste may be stiffened by adding cement.

The physical effectiveness of admixture will therefore depend largely on the character of the original mix. If the cement paste is uniform and plastic, an increase in fine material will not show benefit, but will probably require the addition of water, which may cause loss of strength. If the cement paste is watery, some fine material can usually be added without

addition of water, with general improvement in all properties of the mix.

A few admixtures have cementing properties of their own. When used in combination with portland cement, the resulting mixture usually has a strength about to the contributed by cement plus that contributed by admixture.

Some admixtures have no cementing value of their own, but react with the product of hydration of portland cement to form compounds which add strength to the mixture. Such materials are called pozzolans. (9, 1)

Segregation of Aggregate and Its Affect on Concrete

This is the mechanical re-storing of the concrete into its constituent parts. The large aggregate is separated from the cement mortar and becomes devoid of fine materials. Segregation is caused by bad handling and placing which breaks up the cohesion of the mass of concrete. Chutes, conveyor belts, and other methods of discharging concrete into a coned heap cause segregation. The coarse stone rolls down the heap and segregates at the bottom.

Segregation can also be produced by over-vibration; this causes the large aggregate to sink to the bottom and displace the fine mortar upwards, but such segregation usually takes place only with very wet mixes, really unsuitable for vibration. (1)

Unfortunately, with concrete of good workability there is always the tendency to segregate whenever concrete is transported by wheeled vehicles.

The major portion of any segregation which occurs takes place when the concrete is loaded. (1)

Segregation. Too wet a mixture gives rise to segregation, honeycomb, and an accumulation of laitance, or scum, at the top of each lift. (3)

Conveying. Segregation of concrete occurs because it is not a homogeneous combination, but a mixture of materials differing in particles size and specific gravity. Consequently, as soon as the concrete is discharged from the mixer, there are internal and external forces acting to separate the dissimilar constituents. Any lateral movement such as occurs when concrete is deposited at one point and allowed to flow within the forms, or when the concrete is projected forward by the conveying equipment, cause the coarse aggregate and mortar to separate. If overly wet concrete is confined in some container or in restraining forms, the coarser and heavier particles tend to settle and the finer and lighter materials, particularly the water, tend to rise. These movements continue until they are finally arrested by solidification of the mass through chemical reaction between the cement and water.

(3, 2)

Bleeding

Bleeding is a kind of segregation of the mixing water moves upward due to settlement of aggregate and cement particles. Whether or not bleeding is desirable, depends upon the type of construction and atmospheric conditions at the bleeding surface. Bleeding is controlled mostly by physical and chemical properties of the aggregates may have appreciable effects particularly the size fraction finer than No. 100 sieve. Temperature of the concrete affects chemical reaction in cement and viscosity of water and thus the bleeding. Air-entrainment generally reduces bleeding. Atmospheric conditions may have marked effects, particularly if the rate of evaporation from the bleeding rate, resulting in some cases in unsightly "plastic shrinkage cracking" on surfaces exposed to these conditions.

Two phases of the bleeding phenomenon not necessarily closely related are of interest to users of concrete; (1) the bleeding rate, and (2) the bleeding capacity.

The bleeding rate is measured by the initial rate at which water accumulates at the concrete surface (no evaporation) or by the initial rate of subsidence of the concrete surface. Bleeding capacity is measured by the total subsidence of the surface. Both are affected by temperature of concrete. (12)

EFFECT OF AGGREGATE ON DURABILITY OF CONCRETE

Effect of Aggregate on Weathering Resistance

In an average concrete the solid volume of the fine and coarse aggregate constitutes about 70 per cent of the total, and the quality of this aggregate plays a very important part in the durability of the concrete.

Aggregates that are readily cleavable and structurally weak, or those which are very absorptive, and which swell when moistured are subject to disintegration upon exposure to ordinary weathering conditions. Such aggregate should not be used, as it produces an unsound concrete. Examples of the rocks which may be undesirable for this reason are shales, clayey rocks, friable sandstones, various cherts, and some silaceous materials. (3)

Temperature changes alone have been found responsible for unsatisfactory service records of some concretes, particularly when the changes are rapid it tends to set up large differential strains between the surface and interior of the mass. Certain aggregates having an especially low coefficient of thermal expansion have given poor service at temperatures, causing high tensile stresses in the matrix of cement paste, resulting in; its crazing and cracking. (3)

When water freezes it expands, this expansion can cause a high internal pressure sufficient to disrupt even the strongest concrete. Since, however, concrete can successfully withstand repeated freezing and thawing, it follows that either the water in the concrete is not necessarily frozen even when there is ice on the surface, or else the ice in the concrete was able to expand due to all the voids in the concrete not being filled with water.

For a concrete to be resistant to frost, it should have a low water content, absorption and low permeability so that it will not readily take up water. In addition, the cement paste should have a high permeability so that on freezing of the water, high pressures are not generated within its pores.

(1)

This last requirement is incompatible with a low over all permeability but if the concrete contains small entrained air bubbles, then the distance any water is forced to the first free void space (or air bubble) will compensate for the low permeability of a rich mortar. The concrete should have a relatively high cement content at a water-cement ratio so that as much water as possible is used up combining with the cement during hydration and sufficient strength is achieved to resist stresses set up during freezing conditions. In general, the water-cement ratio should not exceed 0.6, and for road slabs, should be restricted to 0.50. (1)

The greater the number of the air voids, the less will be the damage due to freezing, and the closer they are together, the lower will be the pore pressure.

In any case of freezing, damage arises either from dilation of the paste, or from dilation or breakage of rock particles or from both. (13)

Critical Size and Critical Saturation. In any case, the effect of freezing depends principally on two factors:

1. The size or thickness of the body, and
2. the degree of saturation.

For a saturated specimen, critical size or thickness usually should depend on hydraulic pressure, and hence on porosity, permeability, strength, and rate of freezing.

For any given closed container, the critical saturation point is about 91.7 per cent. For a porous body, the critical saturation point can be almost any figure, depending on size or thickness of the body, the rate of freezing and homogeneity.

A rock particle should have critical size if it has very low porosity or if its capillary system is interrupted by a sufficient number of micropores.

Rock particles larger than the critical size for saturation may fail at various degrees of saturation, depending on the distribution of water content.

Rock particles in hard concrete are liable to produce damage at any degree of saturation above the theoretical limit of 91.7 per cent regardless of size because water is sealed in by paste, each rock particle in concrete is practically a closed container. Rock particles bigger than the critical size for open freezing when saturated are liable to cause damage in concrete at lower than the theoretical critical saturation point. (13)

The resistance of concretes hardened from plastic mixes to freezing and thawing markedly increases as the water-cement ratio is reduced. Table 4 shows three series of freezing and thawing tests on 3-by 6 inch mortar cylinders. For Series A, having constant mix proportions and increasing amounts of mixing water to produce slumps from 0 to 6 inches, the durability shows a progressive reduction as the water-cement ratio and unit water content are increased.

Although groups 1 and 2 are made of non-plastic mortars having low water-cement ratios and high air contents are deficient in strength, as would be expected, they have excellent resistance to freezing and thawing. In Series B, the three different mixes proportions had the same slump and the same unit water content. For these mixes, the durability and strength decrease as the water-cement ratio increases. For Series C, the same mix proportions were used as in Series B, but the water-cement ratio was maintained at 0.51 which caused variations in their unit water contents and slumps. This series also shows that the durability is reduced for the higher water contents. (3)

Influence of Physical Characteristic of Aggregate on Frost Resistance of Concrete. The magnitude of the hydraulic pressure developed in aggregates depends upon their degree of saturation (proportion of total voids space filled with water) and the permeability and size of the aggregate particles. Furthermore, if the degree of saturation of the aggregate is sufficiently high (above the critical 91.7 per cent) so that the remaining air-filled void space cannot accommodate the per cent expansion of water during freezing, then water will be expelled into the paste surrounding the aggregate particles, and potentially destructive hydraulic pressures may be developed there as well as in aggregate. (14)

These major aspects and the important factors involved are as follows:

1. The time required for an aggregate to become critically saturated when in concrete exposed to water influenced by
 - (a) Pore size and porosity of aggregate,
 - (b) Thickness and permeability of protective moisture cover,
2. The various phenomena in the freezing of fully saturated aggregate demonstrating,

COMPOSITION AND PROPERTIES OF CONCRETE

TABLE 4 DURABILITY OF CONCRETE*

Series	Group	Durability	Cycles of freezing and thawing to produce		25 per cent wt loss	Volume of air and water, %			Volume ratio, air water	Mix by wt	Slump, in.	W/C by wt	Cement, pcf	Water, pcf	Compressive strength at 90 days, psi
			0.015-in. expansion			Air	Water	Total							
A	1	Good	360	380	10.5	15.7	26.2	0.67	1:2.75	0	0.29	33.8	9.8	3,300	
	2	to	150	240	5.6	21.5	27.1	0.26	1:2.75	0	0.40	33.4	13.4	6,000	
	3	poor	101	90	3.0	26.3	29.3	0.11	1:2.75	1 3/4	0.51	32.2	16.4	6,000	
	4		83	70	0.1	30.6	30.7	0.00	1:2.75	4 1/2	0.60	31.8	19.1	5,700	
	5		75	60	0.0	31.1	34.1	0.00	1:2.75	6	0.70	30.3	21.2	4,600	
B	6	Good	140	144	3.4	26.3	29.7	0.13	1:2.25	1 3/4	0.44	37.4	16.4	6,600	
	7	to	108	100	3.7	26.3	30.0	0.14	1:2.75	1 3/4	0.51	32.1	16.4	6,200	
	8	poor	82	74	4.3	26.3	30.6	0.16	1:3.25	1 3/4	0.59	27.9	16.4	4,400	
C	9	Good	142	150	6.1	23.2	29.3	0.26	1:3.25	0	0.51	28.4	14.5	5,400	
	7	to	108	100	3.7	26.3	30.0	0.14	1:2.75	1 3/4	0.51	32.1	16.4	6,200	
	10	poor	80	80	0.7	30.1	30.8	0.07	1:2.25	4 1/2	0.51	36.8	18.8	5,900	

* From Ref. 106.

The 3 by 6-inch mortar specimens (No. 4 maximum aggregate) were fog-cured 28 days at 70°F, dried 3 days at 120°F, and then soaked 3 days at room temperature (for absorption tests) before undergoing first freezing for 80 min. The specimens, immersed in water-filled rubber bags surrounded by 5°F brine, reached about 15°F at the center. Thawing required another 80 min in 70°F running water. After each 10 cycles of freezing and thawing the 3-day drying and 3-day soaking operations were repeated.

- (a) Elastic accommodation by aggregate,
- (b) critical size of aggregate (internal hydraulic pressure),
- (c) influence of confining mortar (external expulsion distance and external hydraulic pressure),
- (d) the influence of various factors modifying these effects of freezing; that is, soluble materials, degree of saturation, and freezing point depression in fine aggregate pores.

Time Required for Critical Saturation. The two major factors that appear to determine the time required for an aggregate in concrete to become critically saturated are,

- (1) the nature of aggregate; that is, the porosity and the size distribution of pores in the aggregate,
- (2) the nature of the mortar surrounding, and in very real sense, protecting the aggregate in the concrete from the supply of water external to concrete; its permeability and its thickness; that is, the distance from a piece of aggregate to the surface of the concrete. (16)

Pore Size and Porosity. The size and quantity of the pores control the rate and amount of absorption and, similarly, the rate at which the water can escape from the aggregate particles. (15)

For aggregates with similar pore size distribution, the one with high porosity should require more time to attain any particular degree of saturation than the one of low porosity. (16)

The type of porosity was more important than total pore volume, and that the degree to which the pores become filled with water under natural conditions determined the durability in freezing and thawing.

Report results of freezing and thawing test on gravel having varying degrees of saturation: The more water the aggregate contained, the poorer was the durability.

The aggregates with poorest durability had voids ratios of the small pores several times as great as did some of the most durable materials.

The lack of durability of an aggregate in freezing and thawing is primarily dependent upon its ability to become and stay highly saturated under the given conditions of exposure. The harmful pore size is large enough to permit water readily to enter much of the pore space, but not so large as to permit easy drainags.

According to pressure exerted by freezing water, if no expansion or escape of water is possible, range from 0 psi at 32° F to about 29,00 psi at -4° F. Pressure in this range may be developed in aggregate particles when the saturation is so high that the expansion that takes place when the water freezss. To avoid the development of pressures in excess of the tensile strength of either the aggregate particles or the surrounding mortor, the pore water must be able to flow into unfilled pores or escape from the particle. Escape from the particle may be blocked by a frozen zone around the outside, resulting in the development of high pressures in the interior. Even when flow away from the freezing zone is possible, the hydraulic pressure necessary to cause movement through small capillaries may be so high as to cause disruption of the material.

The most important aggregate properties control the freezing and thawing durability, according to the hypothesis discussed above, are the pore size distribution and the permeability is controlled by the size and continuity of the pores these two porosity characteristics may be considered the important one, with total porosity of secondary importance. (15)

Thickness and Permsability of Mortar Cover. Darcy's Law for flow under hydrostatic pressure and therefore the rate of flow would decrease as the thickness of the membrane increases, and that a highly permeable membrane

would transmit water more rapidly than a membrane of low permeability. (16)

The greater the maximum size of aggregate for a given water-cement ratio, the greater the flow, probably because of the relatively large water voids developed on the under side of the coarser aggregate particles. Aggregates should be sound and of low porosity. A well-graded aggregate is even more important from the standpoint of water-tightness than it is from the standpoint of strength and it is very important that sufficient fine material being used. (3)

The permeability of paste or mortar depends significantly upon the water-cement ratio and the degree of hydration of the cement. For well hydrated pastes, the permeability may be increased by as much as 100 folds as the water-cement ratio is increased from 0.40 to 0.70 by weight. Such difference on the rate at which the mortar membrane will transmit water into an aggregate. (16)

Elastic Accommodation. Under conditions of normal use, the concrete is not subjected to extremely rapid freezing, and therefore a significant portion of the excess of water created in the freezing aggregate has time to escape internal pressures below the tensile strength of aggregate. It is not necessary that all of the excess volume be expelled in order to avoid rupture of the aggregate as the aggregate can elastically accommodate a portion of the excess volume without rupture. The principal of elastic accommodations is clearly revealed by considering the limiting case instantaneous freezing of completely saturated. (16)

The Various Phenomena in the Freezing Saturated Aggregate

In addition to the effect on the length of time the concrete can withstand exposure to water before the aggregate becomes critically saturated and potentially vulnerable to freezing action, the pore characteristics of aggregates and the mortar in concrete significantly influence the response of the critically saturated aggregate to freezing.

The influence of pore characteristics of aggregates and mortar on the reaction of saturated aggregate when frozen under various conditions is summarized in Fig. 10. Three different types of aggregates have been used to demonstrate three different responses to freezing, depending upon the pore characteristics of the aggregate as measured by total porosity (absorption) and permeability.

The different types of aggregates typifying the different types of response on freezing are:

- (a) An aggregate of low porosity, about 0.3 per cent by volume, and perhaps typical of some quartzites, marbles, or trap rocks. Such an aggregate will demonstrate elastic accommodation,
- (b) an aggregate of moderate or high porosity but of low permeability, perhaps typical of chert sand other absorptive aggregates with a fine pore structure, which can cause failure because of high internal pressure; i. e., critical size effects,
- (c) an aggregate of moderate or high porosity but of relatively high permeability, perhaps typical of many limestones, dolomites, sandstones, and other absorptive aggregates with a relatively coarse pore structure which can cause failure because of high external pressures in the surrounding mortar.

Aggregate under such circumstances, none of the water within the particles has time to escape or be expelled. For avoidance of failure, all the volume increase which accompanies the formation of ice from liquid water




	A. Quartzite Absorption = 0.1 per cent	A. Chert Absorption = 2.1 per cent $K_1 \times 10^{-10}$ cm. per sec	A. Dolomite Absorption = 6.7 per cent $K_1 \times 300 \times 10^{-10}$ cm. per sec															
Elastic Accommodation - instantaneous Freezing																		
 $p = \frac{0.09 W_1 E}{3(1 - \mu)}$	$P = 780$ psi (Accommodated)	$P = 17,000$ psi (Fails)	$P = 35,000$ psi (Fails)															
Critical Size - unconfined Freezing at 15 in per hr																		
 $L_{max} = \frac{27.7 K_1 T}{0.09 dw/dt}$	(No Damage)	$L_{max} = 0.5$ in (Fails if Larger)	$L_{max} = 3.3$ in (No Damage)															
Required Expulsion Distance - Freezing While Confined																		
 $DL = \frac{0.09 W_1 L}{SA}$	(No Damage)	<table><tr><th>Cube Size in</th><th>ΔL in</th><th>Cube Size in</th><th>ΔL in</th></tr><tr><td>1/4</td><td>0.0015</td><td>1/4</td><td>0.0040</td></tr><tr><td>1/2</td><td>0.0030</td><td>1/2</td><td>0.0080</td></tr><tr><td>1</td><td>0.0060</td><td>1</td><td>0.0160</td></tr></table>	Cube Size in	ΔL in	Cube Size in	ΔL in	1/4	0.0015	1/4	0.0040	1/2	0.0030	1/2	0.0080	1	0.0060	1	0.0160
Cube Size in	ΔL in	Cube Size in	ΔL in															
1/4	0.0015	1/4	0.0040															
1/2	0.0030	1/2	0.0080															
1	0.0060	1	0.0160															

FIG. 10—Summary of Various Effects of Freezing Saturated Aggregates.

(9 per cent of the volume) must be accommodated elastically within the aggregate.

Table 5 shows that fully saturated aggregates of low porosity do not fail when frozen rapidly because of internal elastic accommodation. Tests were made on 1 by 3/8 by 3/8 inch aggregate prisms frozen at 6° F per second.

TABLE 5.—FULLY SATURATED AGGREGATES OF LOW POROSITY DO NOT FAIL WHEN FROZEN RAPIDLY BECAUSE OF INTERNAL ELASTIC ACCOMMODATION.
1 by 3/8 by 3/8-in. aggregate prisms frozen at 6 F per sec.

Aggregate	Absorption, per cent by weight	Modulus of Elasticity, E, psi	Calculated Stress, psi	Results of Freezing
Limestone.....	1.7	3×10^4	7600	Cracked
Sandstone.....	1.1	2	4400	Cracked
Limestone.....	0.7	5	5500	Cracked
Traprock.....	0.17	8	2000	Cracked
Limestone.....	0.10	6	1500	No distress
Marble.....	0.05	10	700	No distress

The ice pressure, or its counterpart, the tensile stress, which is created within an aggregate can be estimated from the relation

$$P = \frac{0.09 W_f E}{3(1-2 \mu)}$$

where

P = internal ice pressure or aggregate tensile stress required to increase volume of aggregate sufficiently to accommodate expansion, psi,

Wf = Volume fraction of freezable water in aggregate, cu cm per cu cm = aggregate porosity for saturated aggregate, and

M = Poisson's ratio of aggregate, and

E = Modulus of elasticity of aggregate psi.

It may be noted in Fig. 10 that the calculated tensile stress created on instantaneous freezing of a saturated aggregate having an absorption of 0.1 per cent by weight (porosity = 0.3 per cent) is only about 780 psi a stress capable of being withstood by this aggregate. There is a class of aggregates, those that have porosities up to about 0.30 per cent by volume, that are completely invulnerable to freezing action, and can be frozen instantaneously even when completely saturated.

Obviously, saturated aggregates containing significantly greater amounts of freezable water would require correspondingly greater dilations as shown in Fig. 10 for the aggregates having 2.1 and 6.7 per cent absorption by weight. It is seen that the required tensile stresses are much beyond the tensile strengths of these aggregates, and hence that rupture would be expected.

Experimental verification of elastic accommodation during very rapid freezing of saturated aggregates having porosities of about 0.3 per cent by volume (0.1 per cent absorption by weight) or less is shown in Table 5. For such aggregate vacuum saturated and rapidly frozen at 6° F per second, the calculated tensile stresses required for elastic accommodation were 1500 psi or less. Stresses of this magnitude are approximately equal to or below the tensile strength of these aggregates which withstood freezing under these more critical conditions of test. Aggregates with higher porosities and a calculated tensile stresses greater than their tensile strength failed by rupture.

Of course, under conditions of normal use in concrete aggregates are not subjected to such very rapid freezing and a significant portion of the excess volume of water created in the aggregate may be expelled. (16)

Unconfined Freezing and Critical Size of Aggregate. The magnitude of the hydraulic pressure developed in a saturated aggregate particle during freezing depends upon the rate of freezing and the porosity, permeability, and size of the aggregate particles.

If, for simplicity, it is assumed that both the propagation of freezing and the expulsion of water are unidirectional, the maximum hydraulic pressure can be estimated, using Darcy's law as

$$P_{\max} = \frac{0.09d Wf/dt L}{277 K_1}$$

where

P_{\max} = maximum pressure, psi

$d Wf/dt$ = aggregate porosity x rate of linear propagation of
of freezing zone, cm per sec, = rate of freezing of water

L = dimension of aggregate in direction of freezing and expulsion of water, in.,

K_1 = permeability coefficient of aggregate; cm per sec., and

277 = conversion factor, in hydraulic head per psi

Since P_{\max} cannot exceed the tensile strength of the aggregate, this equation can be used to estimate the maximum permissible size or "critical" size of the aggregates as follows

$$L_{\max} = \frac{277 K_1 T}{0.09d Wf/dt}$$

T = tensile strength of aggregate, psi and

L_{\max} = maximum permissible size "critical size" in.

It should be noted that the chert-type aggregate on moderate absorption, but of low permeability (fine pores), has a calculated critical size at this freezing rate of only 0.5 in. However, aggregate of high porosity can have a very large critical size if they also have high permeability.

For the dolomite aggregate shown in Fig. 3, and for the assumed rate of freezing, critical dimension of approximately 33 inches is calculated. (16)

Freezing While Confined by Mortar. To avoid failure during freezing, a saturated aggregate particle having an absorption greater than that which can be elastically accommodated (about 0.1 per cent, and a size smaller than its critical size must be able to expect water into the hydraulic pressures that exceed the tensile strength of the concrete. The factors of primary importance to this mechanism are the freezing rate, aggregate size and porosity, and the permeability and air content of the surrounding paste.

Let us first consider the distance that the expelled water must move into the surrounding paste for volumetric accommodation. We will assume

unidirectional freezing of an aggregate cube with the freezing zone entering one face, and water being expelled from the other five faces. As a simplifying and with further assuming that equal amounts of water are expelled from all five surfaces, and that the expelled water completely fills the air voids for a uniform distance ΔL , around that five sides of the cube L can be calculated as follows:

$$\Delta L = \frac{0.09 W_f L}{5A}$$

where

ΔL = distance required for volumetric accommodation of expelled water, in.,

W_f = volumetric fraction of freezable water in aggregate, cu cm per cu cms.,

L = porosity of saturated aggregate, and,

A = air content of paste, fractional = 0.18 (estimated).

The required expulsion distance depends significantly on the aggregate size and air content of the surrounding paste. Air-entrainment can significantly reduce the required expulsion distance and hence should serve to moderate the high vulnerability of aggregate as unsound when used in non-air-entrained concrete. (16)

The time required for destructive saturation is significantly lengthened by the use of smaller size aggregates.

The hydraulic pressures developed at three important stages of freezing are shown as Stages 1, 2, and 3, in Fig. 3 as follows:

Stage 1. The instant of freezing of the exterior face of the aggregate (that face closest to the freezing surface of the concrete). At this instant,

the permeability of the aggregate, its total porosity, and the freezing rate govern the pressures generated by movement of water through the aggregate into paste air voids present at the aggregate surface.

Stage 2. The instant of freezing of the interior surface of the aggregate when pressures are determined by the rate at which water is ejected from the aggregate upon freezing, the depth of paste saturated by the aggregate (ΔL) and the paste permeability.

Stage 3. The freezing of the paste plus air void system immediately adjacent to this interior surface which is completely saturated for a distance ΔL . This pressure is a function of the freezing rate, paste air content, and the permeability of the paste.

The permeability of the paste, which has a very significant and direct effect on hydraulic pressure, depends upon the water-cement ratio of the cement, and apparently is greatly influenced by any prior drying of the paste.

Calculated hydraulic pressures at the three different stages of freezing of the chert and dolomite aggregates, as shown in Table 6 are based on the several possible paste permeabilities (which vary over 10,00 fold) rather than on a single assumed and perhaps misleading "representative" permeability. The calculations are based on directly measured aggregate characteristics, and estimated factors for rate of freezing (1.5 in. per hour) and air content of paste (18 per cent). (16)

The results shown in Table 6 clearly demonstrate that the permeability of the paste is a major factor influencing the hydraulic pressures developed. These data also indicate that the permeability of a nature paste of 0.50 water-cement ratio can be increased by as much as 60 to 70 fold by partial drying.

TABLE 6—MAGNITUDE OF THE HYDRAULIC PRESSURES DEVELOPED AT THE VARIOUS STAGES OF FREEZING DEPENDS UPON THE PORE CHARACTERISTICS OF THE AGGREGATE AND THE PERMEABILITY OF THE SURROUNDING PASTE.

$\frac{1}{2}$ in. aggregate cubes, air content of paste = 18 per cent.

Paste Characteristics			Hydraulic Pressure Developed at Various Freezing Stages, ^a psi					
Water-Cement Ratio, by weight	Prior Treatment	Permeability of Mature Paste, K_1 , cm per sec (11)	For a Chert Permeability = 1×10^{-18} cm per sec $\Delta L = 0.003$ in.			For a Dolomite Permeability = 300×10^{-18} cm per sec $\Delta L = 0.008$ in.		
			Stage 1 ^b	Stage 2	Stage 3	Stage 1 ^b	Stage 2	Stage 3
0.30	Never dried	1×10^{-13}	1020	6100	18 600	8	43 000	49 500
0.50	Never dried	150	1020	41	200	8	290	700
0.70	Never dried	1200	1020	5	44	8	36	117
0.50	Dried to 79 per cent RH and resaturated	10 000	1020	1	4	8	4	11

^a Unidirectional expulsion of water assumed.

^b See Fig. 8.

It should be noted that whereas low paste permeabilities would create high hydraulic pressure during freezing of saturated aggregate, low permeability would also have an opposite and beneficial effect of decreasing the rate of saturation of the aggregate as previously discussed .

As shown in Table 6, the most damaging stage of freezing, at least that stage developing the highest hydraulic pressure, does not occur during the freezing of the aggregate itself, but rather during the subsequent freezing of the completely saturated paste (paste plus air voids) adjacent to the aggregate.

The hydraulic pressures shown for the first stage of freezing of the two aggregates were calculated, assuming unidirectional expulsion of water. As previously discussed, the hydraulic pressure actually created during the first stage of freezing may be several fold less than the pressures shown because of lateral expulsion of water. However, the relative pressures calculated for the chert and dolomite materials should be correct; that is, the pressure created at the beginning of freezing of the low-permeability chert should be approximately 100 times greater than for the high-permeability dolomite.

It would appear that a saturated porous aggregate of low permeability would be more likely to cause "popouts" in a concrete surface than a saturated aggregate of the same porosity, but of high permeability. In the former case, a high initial hydraulic pressure is created close to the freezing surface of the concrete, precisely at the location where the lowest pressure is required to cause rupture of the concrete and the occurrence of a "popout."

Modifying Factors. If the aggregate is not saturated, or if all of the water does not freeze, either because of the presence of the fine soluble material, or because of the fineness of aggregate pores, then the maximum

calculated parameters for hydraulic pressure, expulsion distance, and critical size must all be modified by appropriate factors.

The hydraulic pressure created during freezing is a direct function of the amount of water which must be expelled from the freezing zone. If the aggregate is totally saturated, the amount of water expelled is approximately 8 per cent of the total volume of water contained. If the porous system is only 91.7 per cent saturated, the remaining unfilled 8.3 per cent of pore space is sufficient to accommodate the 9 per cent expansion that accompanies the formation of ice. Fig. 11 shows the degree to which the hydraulic pressures and expulsion distances previously described are decreased in instances where the aggregate is less.

In addition, other factors modify the effects of freezing. Some of the water contained in the pores of an aggregate will not freeze at 32° F. Water-soluble salts and cement alkalies lower the freezing point of the pore liquid. The freezing point depression due to this effect varies with the materials present and their concentration but usually is not great enough to prevent freezing of the pore liquid at moderate freezing temperatures.

Depression of freezing point also occurs with water in fine capillaries or surface adsorbed. Fig. 12 shows such theoretical freezing point depressions, calculated as a function of equilibrium relative humidity, superimposed on the water adsorption isotherms: It is apparent from this figure that significant amounts of pore water will not freeze in certain aggregates. In the case of the traprock, only about 10 per cent of the water absorbed by vacuum saturation should freeze at -40° F. It should be noted, however, that those aggregates having higher total absorptions have the lower total absorptions have the lower reductions in amount of freezable water due to the effects of capillarity and adsorption. Such reductions in freezable water result in smaller volumes of

water being expelled and thereby moderate the disruptive actions. (16)

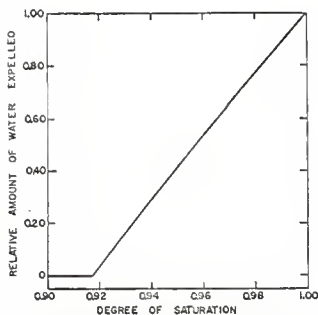


FIG.11—The Relative Amount of Water Expelled and Hence the Disruptive Effect of Freezing Depend Upon the Degree of Saturation of the Aggregate.

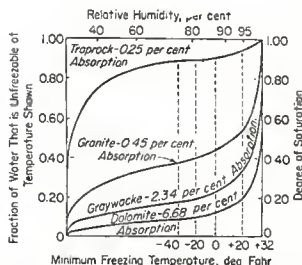


FIG.12—The Fraction of Pore Water Remaining Unfrozen at Various Temperatures Depends Upon the Size of the Aggregate Pores and Can Be Estimated from the Adsorption Isotherm.

For discrimination, the scale for relative humidity has been plotted as proportional to (% RH).

Discussion of Various Test Methods

The actual field durability of concretes made saturation of the aggregates and their response to freezing. Aggregates of high porosity and mortars of low permeability beneficially reduce the rate of saturation of aggregates in concrete, but also have deleterious effects during the freezing of saturated aggregates. For this reason, simple correlations or effects are not to be expected. (16)

The frost resistance of concrete pavement containing this aggregate would undoubtedly be improved by air-entrainment, and free draining subbase, a smaller maximum size of aggregate, and the use of lower water-cement ratio concrete, proper grading of a non-porous aggregate to reduce the permeability. (16)

Conclusions

Based on the preceding discussion, it is believed that the following major conclusions can properly be made:

1. The influence of aggregates on the durability of concrete depends upon the physical characteristics of the aggregates and certain properties of the mortar component of the concrete in a complex but understandable manner.
2. Certain test methods commonly used to evaluate the durability of aggregates for use in concrete are frequently inappropriate and misleading as regards actual field performance of the concrete.
3. Through proper design, based on the principles discussed, much can be done to improve significantly the actual performance of field concrete made with many aggregates rejected by commonly used tests.

Thermal Properties of Aggregate and Its Effect on Concrete

Thermal Properties. Variations in temperature cause concrete to expand when the temperature rises and contract when the temperature falls.

The thermal coefficient of expansion of concrete aggregates has other thermal properties because it can have a direct effect on all types of concrete, whereas the effect of the other properties normally has been concern only with respect to mass concrete and light-weight concrete for thermal coefficients of expansion. An average value of the linear thermal coefficient of expansion of concrete may be taken as 5.5×10^{-6} in. per degree Fahrenheit and it varies 1.2 to 9.2×10^{-6} . Table 7 summarizes the effect variation of aggregate on a 6.1 concrete (12, 17, 28).

Thermal changes are important in mass concrete when cracking is generally due to cooling of the concrete from the maximum concrete temperature is dependent on the initial concrete temperature, the heat of hydration of the cement, the outside temperature, the rate of construction, and thermal change in mass concrete are kept as low as possible by the use of low-heat portland cement, and also by artificial refrigeration. (17)

Effect of Thermal Expansion. There seems to be fairly general agreement that the thermal expansion of the aggregate has an effect on the durability of concrete, particularly under severe exposure conditions or under rapid temperature changes.

THE PROPERTIES OF CONCRETE

TABLE 7

COEFFICIENT OF THERMAL EXPANSION OF ORDINARY PORTLAND CEMENT CONCRETES WITH VARIOUS AGGREGATES

Aggregate	Coefficient of Expansion (per°F)	
	Air Storage	Water Storage
Blastfurnace slag	5.9×10^{-4}	5.1×10^{-4}
Dolerite	5.3	4.7
Foamed slag	6.7	5.1
Gravel	7.3	6.8
Granite	5.3	4.8
Limestone	4.1	3.4
Quartzite	7.1	6.8

(Bonnell & Harper)

Concretes containing the aggregates of the low thermal coefficient failed much more rapidly. Changes in temperature were destructive to concrete

with sudden changes in temperature being much more severe than slower ones; and concretes having higher coefficients of expansion were less resistant to temperature changes than concretes with lower coefficient. It was also determined that the thermal coefficients of expansion of concrete and mortar containing different aggregates varied approximately in proportion to the thermal coefficient and quality of aggregate in mixture. Where the differences between those coefficients exceeds 3.0×10^{-6} caution should be used in the selection of the aggregate combination for highly durable concrete. (18)

The coefficient of expansion depends largely upon the type of aggregate. Concretes made with silicious aggregates have the highest coefficients while those made with limestone have the lowest values. Concretes containing igneous rocks have a coefficient between the two.

The coefficient of expansion of dry and saturated concretes are the same, so that concrete cured in air has a higher thermal expansion than concrete kept in water. (1)

Thermal conductivity is important in three situations: When considering the dissipation of heat from a massive concrete structure, when considering the heat-retaining properties of concrete walls, and also in the allied problem of moisture condensation or sweating.

The rate of dissipation of heat is a function of both the conductivity and the density, while the transmission of heat and the condensation problem depends upon the internal and external temperatures, the relative humidity, the mass or thickness of the concrete, and its conductivity.

From this, it is apparent that to reduce the conductivity the concrete must be maintained dry and its density reduced; i.e., a large proportion of air must be incorporated either in the form of air bubbles or as light-weight aggregate. This leads to the use of a light-weight concrete.

Thermal conductivity varies with the aggregate, and there is a rule of thumb that the coefficient of conductivity is about twice that of the aggregate used. (12)

Thermal Movement. The deterioration of a rock structure may be significantly affected by differences between the coefficients of thermal expansion of aggregate and the cement matrix (8 to 10×10^{-6} per deg. F.) in which it is embedded. (12)

The use of an aggregate with a low coefficient of expansion, (2 to 3×10^{-6} per deg. F.) may lead to disintegration of the concrete, for as the temperature of the concrete is reduced, the cement paste tends to shrink more than the aggregate with the result that tensile stresses are set up in the cement paste which may be accompanied by cracking. Certain limestones have coefficients of expansion of 2×10^{-6} and may cause deterioration in concrete subjected to rapid changes of temperature Fig. 13 shows some experimental values of the thermal coefficient for heat cements and for mortars and concretes containing different types of aggregate. (1, 3)

Thermal Conductivity, Thermal Diffusivity, and Specific Heat. Thermal conductivity, thermal diffusivity, and specific heat are largely interrelated only for mass concrete as used in such structures as large gravity dams in connection with computing concrete placement temperatures and designing systems, and in other thermal calculations aimed at reducing thermal volume change and thus cracking. Thermal conductivity is also of importance in light-weight concrete for insulation purposes, it has been indicated by some that diffusivity may have an important effect on concrete durability.

Thermal conductivity, measured as the rate of heat flow through a body of unit thickness and unit area with unit temperature difference between two

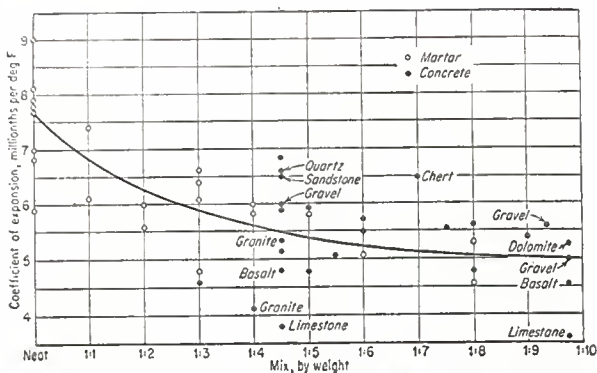


FIG. 13. Thermal coefficients of expansion of neat cements, mortars, and concretes. (From U.S. Bureau of Reclamation [106].)

surfaces is normally expressed in the English system as Btu per square feet per hour per degree Fahrenheit.

Thermal diffusivity is defined as the thermal conductivity divided by specific heat and density and is the physical property of the material which determines the time rate of change of temperature of any points within a body. Its units are square feet per hour.

Specific heat is the amount of heat required to raise the temperature of unit mass of material one degree. Its English unit is Btu per lb per degree Fahrenheit. (18)

Thermal Conductivity of Light-Weight Aggregate. One of the more useful properties of light-weight concrete is its insulating value which depends upon low thermal conductivity for its efficiency. Since thermal conductivity varies directly with density, aggregate of low density produces concrete of lower conductivity. For the same reason as indicated moisture has tremendous effect

on thermal conductivity. In a 1:5 mix of Florida lime rock concrete an increase of moisture from 0 to 5 per cent increases the conductivity by 23 per cent. (18)

The presence of a small amount of moisture in the interior of light-weight concrete greatly increases its thermal conductivity, hence under conditions of continuous or intermittent exposure to moisture, if high degree of insulation is desired, an aggregate (and concrete) of relatively low absorption should be used "Kluge has found pronounced reductions in the thermal conductivity of concrete containing light-weight aggregate, but they influenced more by the reduction in density of concrete than by the characteristics of the aggregate. (15)

Thermal Diffusivity. If, in a mixture such as concrete, the thermal diffusivities and conductivities are the same for each material, the body can be thought of as being thermally homogeneous.

The failure to the relatively high thermal coefficient of expansion of the concrete, which is responsible for surface stress, and to the diffusivity of the gravel which, being higher than the mortar, responds more quickly to temperature change resulting in differential volume change.

Thermal diffusivity of the aggregates apparently has an effect on the durability of concrete, but further work is needed to determine the significance of the effect and to find a practical means for applying this knowledge to the improvement of concrete durability.

Method of Test for Conductivity, Difusivity and Specific heat.

$$K = h c p$$

k = Conductivity in Btu per sq ft per ft per deg. F.

h = Diffusivity in sq ft per hr.

c = Specific heat in Btu per lb per deg. F., and

p = Density in lb per cu ft.

Where conductivity is determined directly, and diffusivity calculated, or vice versa.

Conductivity of concrete and imbeded steel concrete plain and reinforced.

All concretes have a very low thermal conductivity, and herein lies their ability to resist fire.

When the surface of a mass of concrete is exposed for hours to a high heat, the temperature of the concrete one inch or less beneath the surface will be several hundred degrees below the outside.

A point two inches beneath the surface would stand an outside temperature of 1500 to 700 degrees, and points with three or more inches of protection would scarcely be heated above the boiling of water.

The fact that cinder concrete showed a higher thermal conductivity than stone concrete would indicate that its well-known fire-resistive qualities are due, in part at least, to the incombustible quality of the cinder itself.

Thermal conductivity of the gravel concrete was fully as low as that of the trap, but the specimens of gravel concrete cracked and crumbled in many cases when the trap and cinder specimens under similar treatment remained firm and compact.

In the test on the concrete conductivity of imbeded steel with the end projecting from concrete, the same results were found with concrete from all three aggregates with temperature of the end surface of the concrete and the projecting end of the bar 1700 deg. Fahrenheit, a point in the bar only two inches from the heated face of the concrete developed a temperature of only 100 deg. F., while at a point five inches in the concrete the temperature was only 400 deg. to 500 deg. and at eight inches the temperature reached only the heat of boiling water.

From these results reinforcing metal is exposed in progress of fire, only so much of the metal as is actually bare to the fire is seriously affected by it. (19)

Volume changes in freshly mixed concrete are due to water absorption, sedimentation (bleeding) cement hydration, and thermal change, and are influenced by the temperature and humidity of the surrounding atmosphere. Absorption of water by aggregate and reaction between the water and cement both act to decrease the volume. In bleeding, the solid portions of the mix settle, while the clear water rises to the top.

Setting shrinkage may be minimized by the use of saturated aggregate, low cement content mixes, tight and non-absorbant forms, and shallow lifts in placing. (19)

CHEMISTRY OF PORTLAND CEMENT

The chemical composition of ordinary portland cement is as follows:

	<u>Range</u>	<u>Average</u>
Lime (CaO)	59 to 67%	64%
Silica (SiO ₂)	17 to 25	21
Alumina (Al ₂ O ₃)	3 to 9	7
Iron Oxide (Fe ₂ O ₃)	0.5 to 6.1	3
Magnesia (MgO)	0.1 to 4.0	2
Sodium potash	0.5 to 1.3	
Sulphur trioxide (SO ₃)	1 to 3	2

These materials are combined in various chemical compounds (Bogue, 1955) the foremost important of which are,



Di-calcium silicate	(C ₂ S)	2 CaSiO ₂
Tri-calcium aluminate	(C ₃ A)	3 CaOAl ₂ O ₃
Tetra-calciumalumno-Ferrite	(C ₃ AF)	4 CaOAl ₂ O ₃

The tri-calcium silicate (C₃S) and the di-calcium silicate (C₂S) which together form 70 to 80 per cent of the whole, control the strength characteristics of the cement.

A high percentage of C₃S and a correspondingly low amount of C₂S will give a high early strength and will generate considerable heat in the process. The reverse combination results in a slower development of strength and the generation of less heat. The tri-calcium aluminate (C₃A) content is important. It is the least desirable compound, it hydrates rapidly and produces considerable heat during the process, but a cement with a low percentage of C₃A will develop a high ultimate strength, will generate less heat of hydration, will show greater volumetric stability, will have less tendency to cracking and will be more resistant to acid and sulphate attack than a cement with a high C₃A content.

The quantity of lime has to be carefully controlled during manufacture. A large lime content gives a slow-setting product with a high early strength, but an excess may cause unsoundness. The amount of free lime in freshly ground cement is usually about 3 per cent, of which just under one per cent may be unhydrated. The amount of unhydrated in set concrete may cause disruption.

A large silica and alumina content produce a high-strength cement. A high silica content gives slow setting, while high alumina produces a quick-setting cement. A cement with a large amount of a high alumina (approximately 40 per cent) is described as a high alumina cement (q.v. *infra*).

Iron oxide combines with the lime and the silica and is beneficial for those cements high in silica, for it causes a decrease in the C_3A . It also acts as a fusing agent, but if too much iron oxide is present the resultant clinker is difficult to grind. It is iron which gives the gray color to ordinary portland cement.

Magnesia is limited in most British cements to about one per cent as if present in large quantities, it causes unsoundness. The alkalis, soda and potash, are of doubtful value, and are kept to a minimum. They may produce efflorescence in the set concrete; if more than 0.6 per cent is present, which is usual for british portland cements, they will react with certain aggregates.

The sulphur trioxide present is derived principally from the gypsum added to the clinker before grinding, although some sulphur may be derived from the coal used in burning. Sulphur compounds are undesirable, as they tend to cause unsoundness of the cement. (1)

REACTION BETWEEN AGGREGATE AND CEMENT

Attention was first drawn to the reaction between some aggregates and certain cements by Stanton in 1940, although the first structure in which a failure was later traced to this reaction was a bridge built in California in 1920. The failure of this structure was typical of the adverse reactions between cement and aggregates. What happened was that the concrete in the piers was split by extensive expansion and random cracking. Test showed that the expansion which caused the cracking was due to the growth of a silicate gel which had an alkali content (Na_2O) greater than 0.6 per cent. The aggregates which caused the interaction contained Opaline silica and some chalcedonic silica.

The cause of expansion and disruption of concrete by the reaction of cement with aggregate lies in the formation of an alkali silica gel which swells and so produces an expansive pressure. Expansion occurs only when there is a sufficient concentration of reaction is dependent on the presence in the aggregate of silica in reactive form. The silica must be either in a very finely divided state, of which Opaline silica gel is an extreme example, or in an unstable form such as a super-cooled glass, as in volcanic types of rock. The expansion will be greater, the larger the area of aggregate exposed to the alkali. For a given percentage of reactive in the aggregate, the extent of reaction increases with decrease in the aggregate size. (1)

Known reactive substances in addition to Opal are chalcedony, tridymate cristobalite., Zolite huelandite (and possibly ptilolite), glassy to crypto-crystalline rhyolites, dacites, and andescites, and their triffs; and certain phyllites. The formation of the products of the reaction between the alkalies and the aggregate causes abnormal expansions, which, however, sometimes do not take place until two or more years after the concrete has been placed. In a number of cases in recent years, the integrity of important structures has been impaired by these expansions. The obvious steps that may be taken to eliminate this difficulty are two: to detect and eliminate the reactive aggregates, and to limit the alkali content of the cement below some critical value. Some specifications for special cements limit the alkalies to 0.6 per cent. (3)

An expansive reaction between certain types of aggregates and high-alkali cements has been found responsible for random cracking and disintegration of the concrete in many structures. Not only is the cracking unsightly, but it is indicative of a weakened structure.

Several types of aggregates are known to react with high-alkali cement. Opaline silica (amorphous, hydrous silica), which is often present in many different kinds of rocks and many form coatings or encrustations on sand or gravel particles, has been responsible for much disintegration. Other reactive aggregates indicate siliceous limestones and highly siliceous rocks. (1, 20)

A reactive aggregate which causes trouble in concrete may be recognized if it produced expansion within a short time in test specimens made with high-alkali cement. This determination is carried out using a 1:2.25 mortar mix, the aggregate having a specified gradation. Coarse aggregates can be tested by crushing to sand size. After 24 hours of curing, the specimens should be stored at 100 deg. F. in sealed containers, which contain free water, not in contact with the specimens, to maintain the desired humidity. As a result of many tests, the U. S. Bureau of Reclamation allows the use of aggregates which show no more than 0.04 per cent expansion after six months storage, and 0.10 per cent expansion after one year. (14)

Lack of expansion in a short period is no guarantee, however, against a delayed reaction for which no reliable accelerated test has been developed. In general, aggregates known to have, or suspected of, injurious activity should be used only with cement of low alkali content or not at all.

To speed up the determination of potential deleterious reactivity of aggregate, the U. S. Bureau of Reclamation developed a chemical test in which a sample of aggregate is pulverized and treated with a sodium hydroxide solution. The degree of reactivity is determined from the amount of silica dissolved by the solution, and the reduction in alkalinity of the solution. This method has been used successfully in rating many aggregates for which service records and mortar-bar expansion data are available. (3)

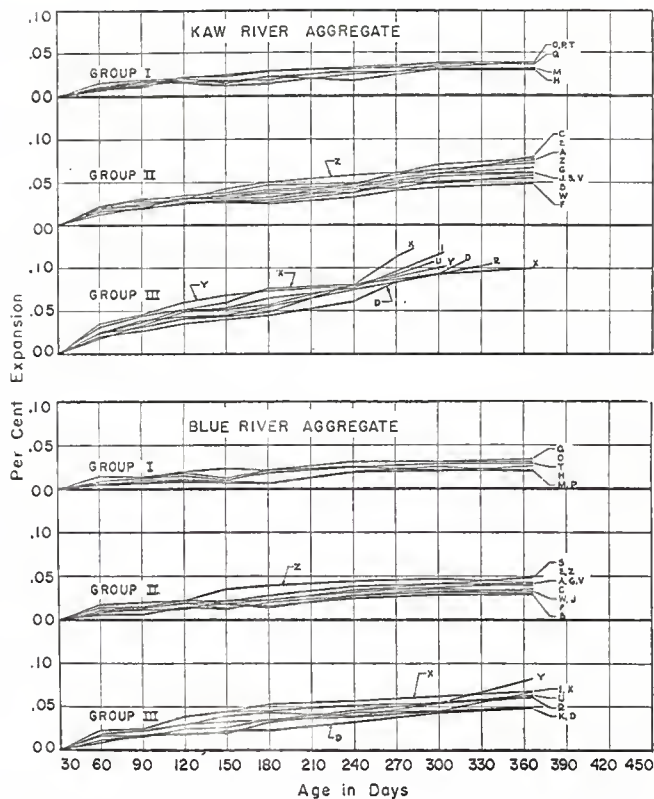


Fig. 11—Expansion Obtained with Different Cements* During Alternate Cycles of Heating-Drying, Cooling-Soaking.

Tests have been made of a number of finely divided pozzolanic minerals for use as correctives by combining with the alkalies while the concrete is still plastic, thus reducing their concentration and preventing later expansive reactions within the hardened concrete. Some test data indicate that the amount of pozzolanic material required is about 20 grams of finely divided reactive silica per gram of alkali in cement in excess of 0.5 per cent. So far the only materials found to be reliably corrective and used in practicable amounts are the Opaline cherts, fly ash, diatomite, calcined Monterey shale, Pyrex glass, and certain other active siliceous materials. In some cases, pumicite has been found effective in reducing the expansions of reactive combinations. (1, 20)

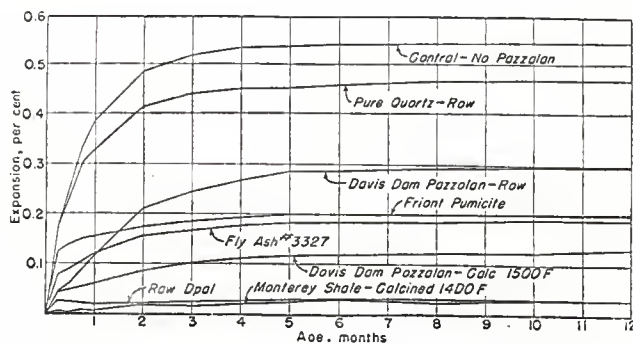


FIG. 15—Pozzolans Variously Reduce the Expansion of Reactive Mortar. (From Meissner (22).)

Mortar Bar Test. Fig. 1 illustrates the expansion of sand-cement

mortars in the mortar bar test as influenced by the type of the sand and the alkali content of the cement. The six cements used in these tests had total alkali contents expressed as Na_2O ranging from 0.45 to 1.4 per cent. These results show that Monrovia sand is not reactive, and does not develop excessive expansion with any of the cements. The Salinas River and Oro Fino sands are reactive, and with this the expansion appears and to be related to the alkali content of the cement. It is not excessive when the sands are used with a low-alkali cement. The rate of expansion of the mortar bar may materially accelerated by increasing the percentage of mixing water used in the preparation of the mortar.

It has been found in most cases, that when natural reactive aggregates are used with different cement, the expansion increases with increasing alkali content of the cement.

The mortar bar test can be reduced also for studying inhibitors that reduce or eliminate the expansion associated with the cement-aggregate reaction. Certain calcined reactive siliceous materials have been very effective in reducing the expansion of the mortars, as illustrated in Fig. 15 and some of them have been used with satisfactory results in large dams. Although a naturally occurring reactive aggregate could be used for such tests, a more uniform supply of reactive materials would be desirable. The Bureau of Reclamation has recommended the use of Pyrex glass, crushed, screened, and recombined to a specified grading, for this purpose. (20)

Effect of Chemical Reaction on Bond. The bond between the aggregate and the matrix has a significant effect on the strength, permeability, and durability of concrete. It is probable that the bond is affected by chemical reactions at the surface of the aggregate, and by the surface texture or other characteristic of the aggregate. There is no suitable direct method

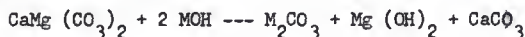
available for measuring this bond between the aggregate and the matrix. The strengths obtained in testing the mortar-making properties of fine aggregates, the compressive strength of concrete cylinders and the flexural strength of concrete and information about the bond. High strengths are indication of a good bond. When it is observed that breaks occur through the aggregate, there is evidence of good bond when breaks occur around the aggregate, and they can be pulled out of their sockets, a poor bond is indicated. The entire problem of the chemical and physical factors that influence the bond between aggregate and matrix is one that deserves further study. (20)

Alkali-Reactive of Carbonate Rock. Although the greatest majority of carbonate rocks are not reactive, certain carbonate rocks have been shown to react and expand rapidly in alkali solution. The reactive rocks can be categorized as follows:

Texture - Partially dolomitized calcilutites; small, isolated dolomite rhombs in carbonate mineralogy - Dolomite limestone, dolomite comprises from 40 to 60 per cent of the carbonate fraction crystallinity of the dolomite does not appear to be an important factor.

Clay Mineralogy - Rocks contain between 10 and 20 per cent clay. All samples were primarily illite, but clay composition does not appear to be critical.

Treatment of the reactive rocks with alkalis was found to produce the following chemical reaction:



in which M represent Kna or Li.

The rates of both expansion and dedolomitization are functions of the calcite dolomite ratio and texture of the rock. Maximum reaction occurs when

calcite and dolomite are present in approximately equal amounts and when both are extremely fine grained.

It is found that expansion of the reactive rocks accompanies the expansion of the dedolomitizing crystals themselves. (21)

Abnormal Stiffening of Concrete Containing Calcined Shale Pozzolan.

False set in portland cement occurs when the liquid phase of the cement for some reaction becomes super-saturated with respect to gypsum and the calcium sulfate in solution precipitation as needless of gypsum and causes abnormal early stiffening. This situation can be brought about calcium sulfate in the form of hemi-hydrate (plaster of paris) going into solution faster than the hydration C_3A can react with the sulfate already in solution to form calcium sulfoaluminate. Calcium sulfate, usually in the form of gypsum is interground with portland cement clinker in order to minute hydrates which cause flash set, usually. All other things being equal, the more C_3A there is in a cement, the more calcium sulfate is a very small amount of C_3A has a higher than optimum SO_3 content, especially when part of the SO_3 is present as hemihydrate, false set is likely to occur.

Another factor that may influence false set is the fineness of the cement or pozzolan. The finer the cement or pozzolan is ground, the faster the SO_3 will go into solution. Tests made by the National Bureau of Standards indicated that the project cement (RC-489) had an air permeability specific surface of 3370 sq cm/g. Fineness tests run on the project pozzolan at WES indicated that its air-permeability specific surface was 25,260 sq cm/cu cm. There fore, it follows that any soluble sulfate that was present in the pozzolan calcined at 1250° F was present primarily as semi-hydrate and soluble anhydrite. The soluble sulfate in the cement was present as gypsum. The

SO_3 content of the cement was probably somewhere near the optimum for the fineness, and C_3A content of the cement. Therefore, when the cement was partially replaced with a pozzolan containing sulfate, more soluble than those in the cement itself, the optimum SO_3 content might have been exceeded with the result that abnormal stiffening, or false set, occurred. This appears to be the most logical explanation for the premature stiffening of the John Day Dam project, based on the present test results. If this were, in fact, what happened when the pozzolan test results calcined at 1250 F was used, the reason that it did not happen when the pozzolan calcined at 1600 F was used, even though this pozzolan had the SO_3 content as the lower-temperature calcined material, was related to the crystalline form of the sulfate in the 1600 F calcined material. The higher calcining temperature converted most of the hydrated calcium sulfate (gypsum) present in the raw shale to dead burned gypsum or natural anhydrite, a somewhat more insoluble form than either of the hydrates. When this pozzolan was used as a replacement for part of the cement, the SO_3 in the pozzolan did not go into solution as quickly, and hence the conditions that make for false set did not exist.

The minimum temperature for complete dehydration of hydrous calcium sulfate to anhydrous calcium sulfate is given as 163 C gypsum present in the shale should have been converted to insoluble anhydrite since 1250 F is well in excess of 163 C. The sample of 1250 F is pozzolan did not behave as if all the gypsum it (25) originally contained had been converted to insoluble anhydrite. Why it so behaved is not entirely clear, but the possibilities include:

(a) The calcining temperature may have been lower than 1250 F.

(b) The rate at which material was processed may have been such that not all the material stayed in the kiln long enough to be heated to the nominal calcining temperature, and

(c) Totally inclosed masses of particles of gypsum may have been restrained from complete dehydration because they were inclosed, and when the processed material was crushed, it yielded soluble anhydrite or semi-hydrate particles or a mixture of both.

In any case, the conclusion is inescapable that particles of calcium sulfate that were not in the form of insoluble anhydrite were present in the 1250 F pozzolan as received for test, and these particles for two hours at 1250° F as a part of this investigation. (22)

Effect of Entrained Air on Concrete

Air Entrainment. The phenomenon that occurs as a result of the inter-mixing of air-entraining material in mortar or concrete. (23)

Air-Entraining Admixture. Air-entraining material added to a concrete or mortar mixture at the time it is batched for mixing. It was recognized from early laboratory tests that greatest resistance to frost action occurred when the entrained air amount to about three per cent of the total volume.

The total air content of the mixture varies through wide range, but the air content of the mortar in the concrete mixtures is essentially constant at 910 per cent. As the maximum size of coarse aggregate increase, less mortar and paste are required. Therefore, change in total air content with change in maximum size of coarse aggregate is proper. (23, 3)

Factor Affection Air Entrainment.

1. The sand between B. S. Sieve No. 25 and No. 100 reacts with air entrainment agent. (1)
2. Coarse sand has little effect.
3. Finer material such as that passing the No. 100 mesh sieve, together with silt, dust and cement powder, all inhibit air-entrainment, so that it is

difficult to entrain in rich mixes. The finer the cement is ground the less is the amount of air entrained.

4. Well rounded soft sand are more efficient at air entraining than angular, sharp sands.

5. The percentage of sand in the mix between B. S. Sieve No. 25 and 52 increases the amount of air entrained. (1, 23, 24)

6. The larger the aggregate the less the amount of air entraining additive needed to give same result. (1, 20)

7. Organic materials cause entrainment of large quantities of air in concrete. (12)

The Effect of Entrained Air on the Properties of Concrete.

1. Increases the frost resistance of concrete. (1, 23, 24, 25, 26).

2. Improves the workability and is accompanied by less segregation and bleeding, and results in a more homogeneous mix. (1, 3)

3. Increases the plasticity and generally improves its handling. (1)

4. Reduces the compressive strength. (See Fig. 16)

5. Concrete is able to withstand many cycles of freezing and thawing before disintegration if its water content is initially below about 90 per cent saturation. As the saturation is reduced, the water is held by finer capillaries, and the temperature at which it will freeze becomes progressively lower, because the surface tension in these small capillaries holds the water in state of stress and reduces its freezing point. (1)

6. As the result of the plasticity, it is possible to reduce the quantity of mixing water and to reduce the percentage of sand to total aggregate by about 1.3 times the air content. (3)

7. Both flexural and compressive strength decreased with increased air content. In general, compressive strength decreased $2\frac{1}{2}$ per cent, and

flexural strength one per cent for each per cent increase in air content. (26)

8. The addition of 30 per cent of limestone coarse aggregate to the sand-gravel aggregate reduced the amount of air entrained, increased the strength, and showed excellent resistance to freezing and thawing for concretes having air content five per cent or more. (26)

9. The shrinkage of concrete with sand-gravel aggregates and blends of Types I and IA cements moist-cured 7 days and then stored in the air of the laboratory at 75 deg. F, and 50 per cent relative humidity increased with increase in air content. (26)

10. For constant cement content and consistency, the reduction in strength with entrainment of air decreases as the maximum size of aggregates decreases due to greater reduction in water requirements possible with the smaller size aggregates.

11. For a particular consistency, the reduction in strength with entrainment of air decreases with a decrease in cement content, due to the greater reduction in water requirements possible in the leaner mixes. These larger reductions in water requirements often result in increases in strength as air is entrained in the lean mixes. (26)

12. In all cases, the entrainment of air increases the resistance of concrete to freezing and thawing, and to surface scaling resulting from the use of salts for ice removal. (26)

13. For the air-dried concretes at a particular maximum size of aggregate there appears to be little effect of cement content on the optimum concrete air content.

The general effects of air entrainment are to increase workability, decrease density, decrease strength, reduce bleeding and segregation and increase durability.

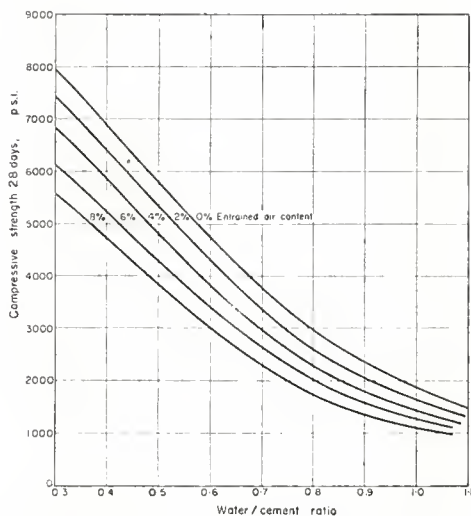


Fig. 16 Effect of air entrainment on compressive strength.

EFFECT OF AGGREGATE ON CONCRETE STRENGTH

Strength

The crushing of average rock aggregate is higher than the strength of the concrete made with them. The maximum crushing strength of concrete is about 10,000 to 15,000 psi. which is about the minimum strength of average rock aggregate, which varies from about 10,000 to 50,000 psi. The bond between the cement and aggregate controls the concrete strength with all but the weakest aggregate. Weak aggregates such as weakly-cement sandstones, some expanded clay and light-weight materials such as vermiculite, place a limit on the attainable strength.

Although the aggregate bond controls the strength this does not mean that failure does not take place through the aggregate. Where the bond is strong then the shear strength which can be mobilized around the surface of the aggregate may exceed the shear strength across the aggregate, and in such a case the failure plane lies through the aggregate. But where the bond is poor, the failure will be along the surface of the aggregate particles. (1)

The effect of the type of aggregate of normal weight and given gradation on compressive strength of concrete is minor, probably because all such aggregates are far stronger than the paste. With equal water-cement ratio, concrete containing angular or rough-textured aggregate will usually be somewhat stronger than containing rounded or smooth aggregate. With equal cement contents, however, somewhat more water is required for workability when angular or rough aggregates are used, and the net effect is that for equal workabilities the concrete strengths are not greatly different.

Lightweight aggregates are relatively weak, the strength varying roughly with unit weight, and often the strength of lightweight concrete is governed

by that of the aggregate. If lightweight aggregate is used as both coarse and fine aggregate, the partial upper limit of compressive strength appears to be of the order of 5,000 psi regardless of cement content. (1)

The shape of the aggregates, and the aggregate-cement ratio all affect strength of concrete. A concrete containing crushed rock will have a higher strength than a similar concrete made with a rounded aggregate. These facts can be explained by visualizing the failure of concrete as being due to shearing action through the mortar. It follows that shearing through the aggregate will take place if this forms the weakest path, but the shear path will be round the aggregate if the aggregate surface is smooth and the resistance generated round the aggregate is less than that through it. The shear force and hence the strength will also be larger if the aggregate forms a larger proportion of the whole, or if larger aggregate is used. The larger the ratio of aggregate to cement, the higher is the strength for the same water-cement ratio and workability. (1)

The strength of concrete is its resistance to rupture, and may be measured in a number of ways. Thus we have the strength in compression, in tension, in shear, and in flexure. All these define strength by reference to a method of testing; some methods determine basic properties of the material while others do not. Concrete is a brittle material with a compressive strength about ten times its tensile strength.

Tensile and Flexural Strength. The water-cement ratio is the primary factor that governs the tensile and flexural strength of concrete. The characteristics of the aggregates have greater effect on the tensile and flexural strengths than on the compressive strength because of the greater demand on bond between the cement paste and the aggregates.

The tensile strength of a concrete is one-tenth to one-twelfth of its compressive cylinder strength. The modulus of rupture of an unreinforced concrete beam is one-fifth to one-seventh of its compressive strength; failure in bending is by rupture of an un-reinforced concrete beam one-fifth to one-seventh of its compressive strength; failure in bending is by rupture of the extreme fibers in tension. (27)

Shear Strength, Diagonal Tension. When concrete specimens are subjected to direct (punching) shear of the apparent shear strength is equal to or greater than one half of the compressive strength, depending upon the richness of the mix. However, the failure is probably not in shear, but in tension, a phenomenon concrete to brittle materials. For instance, a concrete beam can be so loaded as to develop diagonal cracks in the regions of high shear indicating that the shearing force have combined to strength of the concrete. The apparent shear strength of concrete then is of less significance than is diagonal tension to the reinforced concrete designer. (27)

Failure load be made by assuming that the concrete in resisting failure, generates both cohesion and internal friction, which depends on properties of aggregate. It can be shown that with such an assumption the basic shear strength is given by the Coulomb equation,

$$S = c + \sigma \tan \phi$$

where

S = shear strength, c = cohesion, σ = inter-granular stress

ϕ = angle of internal friction

Effect of Aggregate Size on Properties of Concrete

There is generally accepted theory of long standing that increasing the maximum size of aggregate yield improved concrete strength. There is different

relationship between strength and water ratio existed for different sizes and that "for a given water-ratio strength becomes less as maximum size of coarse aggregate is increased. So that, it seems probable that the relationship between strength and maximum size will vary depending upon the characteristics of the aggregate." (28)

Results indicate that increasing the maximum size of coarse aggregate may not necessarily be beneficial to concrete-ratio strength relationship for smaller sizes within limitations, is sufficiently higher than for larger sizes that higher strength are developed even for the same cement content and consistency.

The effect of maximum size of aggregate on compression strength for non air-entrained concrete will be for 6 and 8 sack concrete the strengths for maximum size of $1\frac{1}{2}$ and $2\frac{1}{2}$ inch were always lower than $3/4$ inch size and generally lower than $3/8$ inch. For 4 sack concrete there was with one exception, a general upward trend in strength with increased maximum size. The exception was the 91 day concrete made with the $2\frac{1}{2}$ inch aggregate.

The same type of relationship is shown for the air-entrained concrete, with the smaller sizes appearing in an even more favorable light. These data again show a progressive reduction in strength with increased maximum size for 6 and 8 sack mixes. Even in the 4 sack concrete, maximum sizes of $3/4$, $1\frac{1}{2}$, and $2\frac{1}{2}$ inch all gave substantially the same strength.

The flexural strength in similar fashion. The pattern of the relationships is the same as for compressive strength, although the differences in strength, proportionally, are not so great. (29)

Test involved coarse aggregates two types and gradings ranging from $3/8$ to $2\frac{1}{2}$ inch maximum size, with concrete tested for both flexural and compressive strengths.

In the first group of tests, maximum strengths being lower for the $1\frac{1}{2}$ and $2\frac{1}{2}$ inch sizes. This was in spite of normal reductions in mixing water which caused the water-cement ratio to become less as size of aggregate increased with maximum strength in both flexural and compression were secured with coarse aggregate of about $3/4$ inch maximum size, strengths being lower for the $1\frac{1}{2}$ and $2\frac{1}{2}$ inch sizes. This was in spite of normal reductions in mixing water which caused the water-cement ratio to become less as size of aggregate increase, with maximum strengths being for a maximum aggregate size of $3/4$ inch.

Additional confirmation that large size of concrete aggregate may reduce strength was secured in limited tests of concrete screened to remove large aggregate particles. In comparisons involving normal and air-entrained concrete of two different slumps, the proportion of concrete passing a $3/4$ inch sieve tested about 7 per cent stronger in compression and 15 per cent stronger in flexure than the original concrete made with $1\frac{1}{2}$ inch maximum size coarse aggregate.

These tests suggest that, so far as strength is concerned, too much emphasis may have been on the desirability of using large sizes aggregate.

In spite of the lower mixing water requirement for large maximum sizes, strength may actually be less than for the intermediate or small sizes precisely why this should be so is not evident, probably it is related to the greater surface area for bond and cross-sectional area to resist shear has the added advantage to providing more easily placed concrete with less segregation and more reproducible strength tests. (30)

In selection of a smaller maximum size of aggregate for test concretes. The results of recent investigations reveals quite conclusively that frost resistance of concrete is dependent primarily upon the amount of freezable

water within the concrete and characteristics of the air voids. Intentionally or non-intentionally entrained, such as distribution, spacing and total amount.

Freezing and thawing tests of aggregate indicate that the resistance of the aggregate to the action of freezing and thawing decreases as the size of aggregate increases. This effect of size could be of importance in determining the frost resistance of concrete. (14)

With the largest particles not over 3 inch in diameter, it may be stated that the larger the maximum size of the aggregate the denser and stronger will be the concrete provided other influencing factors are eliminated. (31)

Where no physical restrictions are placed upon size, the use of larger maximum sizes gives greater economy in the use of cement.

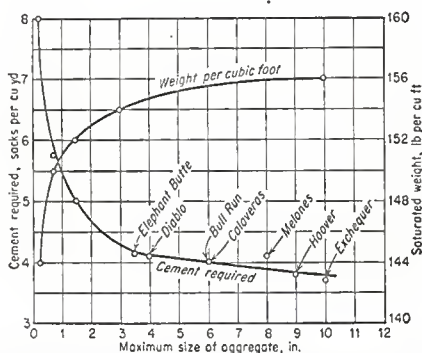


FIG. 17 Effect of size of aggregate upon cement requirement and unit weight of concrete of given water-cement ratio and consistency. Water-cement ratio = 6.5 gal per sack of cement. Slump 3 to 5 in. (Portland Cement Association.)

Size larger than 6 inch gives rise to difficulties in handling and placing.

The use of a larger maximum size of aggregate reduces the voids in the coarse aggregate and results in a lower sand requirement in the combined aggregate. (3)

According to the new theory that when the maximum size of aggregate increases, the strength is not necessarily increased, it appears that the above, Fig. 17 is not quite dependable. If the maximum aggregate size can be reduced, the following advantages will accrue.

1. Workability of the concrete will be improved and there will be less likelihood of defects and rocks in concrete.

2. There will be less wear on concrete mixers and equipment.

3. Water tightness of the concrete will be improved, the danger of bleeding and separation under larger fragments of aggregate and reinforcing having been reduced.

4. It is known from experience that when the maximum aggregate size is reduced, the concrete is better able to resist temperature variations; e.g. freezing and thawing. This is probably due to a decrease in the internal stresses which are caused by the different thermal properties of the binder and aggregate. (14)

(28, 29) summarized the following conclusions:

1. At given water ratio within the range employed in most structural concrete, smaller maximum size aggregate will tend to produce higher concrete strength than larger one.

2. The larger size will require less mixing water and hence for a given cement factor, will produce concrete of lower water-ratio than smaller sizes.

3. The advantages of smaller aggregate in the water-ratio strength relationship may or may not be sufficient to offset the effects of its higher mixing water demand. It appears that optimum maximum size, so far as strength is concerned, will vary from different aggregates, different cement factor, different test ages, and probably other conditions.

4. A realistic appraisal of the recent data for several different aggregates must lead to the conclusion that size of aggregate, characteristic within a reasonable range is less importance to concrete strength than other aggregates.

5. In all air-entrained concrete and all but the leanest non-air-entrained concrete strength was progressively reduced as maximum size was increased above 3/4 inch.

6. The preliminary drying shrinkage data indicate increased volume change resulting from use small size aggregate.

Within a reasonable range, is of less importance to concrete strength than other aggregate characteristics, even in the leaner mix where the larger aggregate gave higher strength the advantage was inconsequential in relation to strength differences between aggregate of the same size from different sources.

Effect of Density on the Compressive Strength of Concrete

If the kind of cement and the proportion of cement per unit volume of concrete is maintained constant and if the consistency, shape of aggregate particles age, and method of curing the concrete are the same, the strength will increase with the density.

Experiments have shown the strength varies directly as the ratio $c/1-p$ the equation being $S_c = p \left(\frac{c}{1-p} - n \right)$. Here S_c = unit compressive strength,

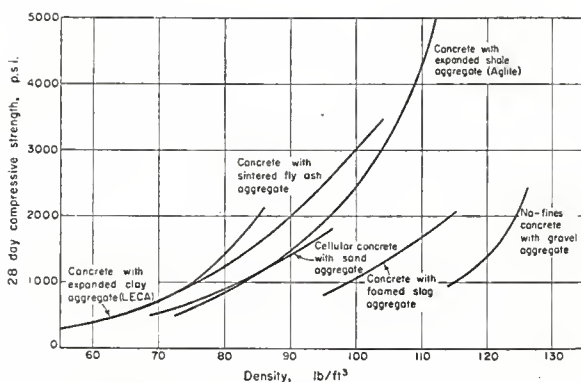


Fig. 18 Relationship of strength and density for various lightweight concretes.

c = volume of cement grains in a unit volume of concrete, p = density of concrete factors mentioned above.

Bond Characteristics and Surface Coatings

The capacity for bonding with the cement paste is one of the most important attributes of an aggregate and the surface texture is probably one of the most important single properties of an aggregate which affects the concrete strength.

An aggregate should be clean and free from unwanted materials whether it be chemical impurities, rock flour or other surface coatings. Surface coatings are usually detrimental because the aggregate bond is reduced, and organic matter which is a common coating of sands react detrimentally with the cement and delay the set. There is little trouble due to reactive aggregates, but elsewhere may natural coatings contain reactive minerals; e.g. opaline silica, which react with the cement alkalis.

The usual coatings are clay, silt and organic matter. Aggregates coated with these materials can be made satisfactory by washing but even so, frequent inspection after washing is necessary to insure that they do not still contain clay balls or organic matter.

Some aggregate may be encrusted with calcium carbonate, iron oxide and perhaps gypsum. If the carbonate is firmly adhered to the aggregate it may improve and not reduce the bond strength, but iron oxide may cause staining and may, by oxidation, cause excessive volume change in concrete. (1)

It is customary to specify permissible bond stresses as percentage of the compressive strength of concrete.

Bond strength varies considerably with type of cement, admixtures and water cement ratio, all of which influence the quality of the paste.

Bond strength is reduced by alternations of wetting and drying, of freezing and thawing, or of loading. (3)

Influence of Aggregate on Creep

Creep is affected by the type of aggregate in much the same manner as in shrinkage - sandstone and basalts may produce large amounts of creep; lesser amounts result from using flint gravel or low-absorption limestone. Creep is reduced by using a large aggregate and ensuring a small voids ratio in much the same manner as for shrinkage. (1)

The large variations in creep were not due to the moisture conditions of the aggregates. It is possible that variations in crystalline slip particles shape, surface texture, and pore structure of the aggregates may have some influence.

Although the data are somewhat conflicting, it appears that the greater the maximum size of an aggregate graded uniformly from fine to coarse, the less the creep of the concrete. This is particularly true when the water-cement ratio is reduced, as is normally the case when an aggregate of higher fineness modulus is used. (3)

Effect of Aggregate on Shrinkage

The aggregate has a two-fold effect on shrinkage; on the one hand, it forms a kind of semi-rigid skeleton which shrinks less than the surrounding cement paste, while it also disperses the paste and so reduces the shrinkage per unit volume. Rich concretes shrink more than lean concretes. To achieve minimum shrinkage, therefore, concrete should contain the maximum possible amount of large aggregate consistent with other desirable properties such as workability.

TABLE 8 EFFECT OF MINERAL CHARACTER OF AGGREGATE
UPON CREEP*

<i>Aggregate</i>	<i>Creep after 5 years, millionths†</i>
Sandstone.....	1,300
Basalt.....	1,110
Gravel.....	950
Granite.....	840
Quartz.....	790
Limestone.....	550

* From Ref. 1251.

† 4 by 14-in. cylinders loaded to 800 psi after moist curing to age 14 days. Storage in air of 50% R.H.

TABLE 9 EFFECT OF MOISTURE CONDITION OF STORAGE UPON CREEP*

<i>Storage condition</i>	<i>Creep after 5 years, millionths</i>
50% relative humidity.....	850
70% relative humidity.....	710
100% relative humidity.....	350
Water.....	300

* From Ref. 1251.

Aggregate-cement ratio, 5.67 by weight. Water-cement ratio, 0.89 by volume. Age at loading, 28 days. Sustained stress, 800 psi. Specimens, 4 by 14-in. cylinders.

The type of aggregate is important because its moisture movement will affect the total shrinkage; aggregates such as sandstone, basalt, and some granites, which may swell or shrink appreciably with change in moisture content, produce a concrete with more shrinkage than concrete containing flint, gravel, dolomite or limestone of low absorption. Indeed some dolomites may have such a high moisture movement as to result in disruption of the concrete. The mineral character of the aggregate also affects the shrinkage; hard, dense aggregates with a high modulus of elasticity result in less shrinkage.

Beside the type of aggregate, the grading is important. The grading used should result in a mix with a high density using the maximum size of aggregate. (1)

The ability of normal aggregates to restrain the shrinkage of a cement paste depends upon (1) extensibility of the paste; (2) degree of cracking of the paste; (3) compressibility of the aggregate; (4) volume change of aggregate due to drying.

In Table 10 is shown the shrinkage of heat cement in comparison with corresponding shrinkage of the same cement diluted with a single sieve size (No. 4 to 3/8 inch) of gravel and crushed limestone, respectively. The reduction in shrinkage due to the aggregate is greater than would be expected considering its relative volume. It is possible that internal cracking of the paste due to the restraint of the aggregate is a factor.

The effect of the size of aggregate upon shrinkage is in Table 11. For all the smaller sizes of aggregate, the shrinkage is fairly uniform; indicating that for these sizes, there probably is no internal cracking. However, it is possible that for these concretes the shrinkage is reduced by cracking of the paste when the size of aggregate exceeds about 1/4 inch.

TABLE 10 EFFECT ON SHRINKAGE OF ADDING AGGREGATE TO CEMENT PASTE*

Aggregate	Parts by wt			Paste, per cent by volume	2-year shrinkage in air of 50% R.H., millionths
	Cement	Aggregate	Water		
None (neat paste)....	1	0.0	0.40	100	2,705
Gravel.....	1	2.5	0.40	44	725
Crushed limestone....	1	2.6	0.40	44	417

* From Ref. 1204. Specimens were 3 by 6-in. cylinders.

TABLE 11 EFFECT OF ADDING VARIOUS SIZES OF DOLOMITE AGGREGATE TO CEMENT PASTE*

Aggregate size	1-year shrinkage in air of 50% R. H., millionths
None (neat paste).....	2,710
No. 48-No. 28.....	1,190
No. 28-No. 14.....	1,240
No. 14-No. 8.....	1,220
No. 8-No. 4.....	1,160
No. 4- $\frac{3}{8}$ in.....	940
$\frac{3}{8}$ in.- $\frac{1}{4}$ in.....	690

* From Ref. 1204.

Mix, 1:1 by weight; water-cement ratio 0.40; cylinders 3 by 6 in.

For a given maximum size of aggregate, a wide range of acceptable gradations of aggregate, including continuous and gap gradings, as well as unusual gradings with fines omitted, has very little effect on shrinkage.

Large differences in concrete shrinkage result from the use of different aggregates, as shown in Table 12. In general, concrete low in shrinkage often contains quartz, limestone, dolomite, granite, or feldspar, whereas those high in shrinkage often contain sandstone, slate, basalts, trap rock, or other aggregates with shrink considerably of themselves or have low rigidity to compressive stresses developed by the shrinkage of the paste.

TABLE 12 EFFECT OF TYPE OF AGGREGATE OF A SINGLE SIZE ON THE SHRINKAGE OF CONCRETE*

Aggregate	Absorption, %	1-year shrinkage, in air of 50% R.H., millionths
A. Mixed gravel.....	1.0	560
B. Slate, hand-picked from A.....	1.3	680
D. Granite, hand-picked from A.....	0.8	470
E. Quartz, hand-picked from A.....	0.3	320
F. Sandstone.....	5.0	1,160
G. Solid glass spheres.....	0	250
H. Limestone.....	0.2	410

* From Ref. 1201.

Mix 1:2.5, water-cement ratio 0.40, aggregate size $\frac{3}{16}$ to $\frac{3}{8}$ in., and specimens 3 by 6-in. cylinders.

The shrinkage of the aggregate themselves may be of considerable importance in determining the shrinkage of the concrete, as shown in Table 13 by the volume change, for various building stones when alternately wetted and dried. The differences between the various grades of sandstones alone are noteworthy. (3)

Tests indicate that concrete in actual structures shrinks about 0.05 per cent, as soon as it is allowed to dry out. The corresponding expansion, if kept wet, is much smaller, possibly about 0.01 per cent.

Professor A. H. White has shown that concrete, even when twenty years old, expands if wetted and shrinks if dried, and that with rich mortars these variations cause changes much greater than those due to temperature. Successive long immersions with intermediate dry periods cause progressive expansion. A smaller bar cut from a sidewalk after 20 years service elongated 0.175 per cent by successive immersions at room temperature. (29)

A shrinkage of 0.080 per cent after one year in 1:2:4 concrete beams 4 by 5 inch by 4 ft. long, mixed with 3/4 inch limestone, and reinforced with about 0.3 per cent steel. The total shrinkage does not appear to be affected by any temporary method of storage; concrete stored in air begins to shrink at once, but shrinkage of concrete stored for a few months in water or under moist cloths proceeded shrinkage rapidly enough upon exposure to dry air to make up for the lost time. Beams in wet storage showed a tendency to expand while wet, and beams in dry air expanded rapidly if transferred to water storage.

German test of concrete specimens mixed with ordinary coarse aggregate setting in air give shrinkage of 0.032 per cent, or not much more than one-third of above results. The rate of shrinkage was about the same in both cases; two-thirds of the total being attained in forty days with a more gradual increase to the maximum which was reached in from 200 days to one year. (29)

Reinforcement for Temperature and Shrinkage Stresses. All masonry is subjected to temperature cracks, but when they are distributed in the many joints between bricks or stones they do not show as plainly as on the smooth surface of concrete.

Expansion from a rise in temperature rarely causes trouble except at angles where the lengthening of the surface may produce a buckling or a sliding of one portion of the wall past the end of the other. In a building, the walls and floors are generally so well bonded together and free to move as a unit, that no provision need be made for expansion. In a structure like a square reservoir, the effect of expansion must be taken into account in the design to prevent failure at the corners.

Reinforcement properly placed distributes the contraction stresses so as to make the cracks very small, practically invisible, but it does not prevent them entirely. (29)

Effect of the Aggregate on Shrinkage of Concrete and Hypothesis Concerning Shrinkage. Derivation of Formula: In deriving the formula, consideration is first given to effect on shrinkage of one small, spherical particle of aggregate in a large body of concrete, the surrounding concrete considered to be a homogeneous material. This approach is concerned with the effect of fillers on elastic properties. The restraining effect of aggregate on shrinkage of concrete is on the assumption that both the particles and the rest of the body are elastic, an expression is derived for reduction in overall shrinkage of the body due to the one small, non-shrinking particle. This provides a formula for the effect of adding each previously is assumed to be homogeneous. This formula is then expressed in differential equation from and an integration made to obtain the final formula.

It will be expedient to consider that the small, spherical particle is at the center of the body of concrete which is also a sphere. If the particle is small compared with the shortest distance from it to the concrete surface, no great error will be introduced by treating the concrete as spherical with a radius equal to that distance. The restraint of the small sphere as the

large sphere tends to shrink will cause the following stresses in the large spheres:

$$\sigma_r = -\frac{pa^3}{r^3} \frac{b^3 - r^3}{b^3 - a^3} \quad (1)$$

$$\sigma_t = \frac{pa^3}{2r^3} \frac{b^3 + 2r^3}{b^3 - a^3} \quad (2)$$

Where σ_r = normal stress in the radial direction

σ_t = either of two normal stresses perpendicular to the radius

r = radial coordinate

a = radius of inner sphere

b = radius of outer sphere

p = unit pressure between inner and outer spheres

Under these conditions of spherical symmetry, radial displacement of any point in the outer sphere caused by the restraint of the inner sphere, and referred to the unrestrained position, is

$$\delta = \frac{r}{E} \left[(1 - \mu) \sigma_t - \mu \sigma_r \right] \quad (3)$$

where E and μ are Young's modulus and poisson's ratio, respectively, for the outer sphere.

From Eq. (1), (2) and (3)

$$\delta = \frac{pa^3}{Er} \left[\frac{1 - \mu}{2} \frac{b^3 + 2r^3}{b^3 - a^3} + \mu \frac{b^3 - r^3}{b^3 - a^3} \right] \quad (4)$$

The restraint of the inner sphere has reduced the volume shrinkage of the total body by the amount

$$\delta_{r=b} = \frac{3p\Delta V}{E} \left(\frac{1 - \mu}{2} \right) \frac{3b^3}{b^3 - a^3} \quad (5)$$

where $\Delta V = 4/3 \pi a^3$ is the volume of the small sphere.

If the restraint had not been present, the body would have reduced in volume by $3SV$, where V is its total volume and S is the unit linear shrinkage. The reduction in volume shrinkage will therefore be designated as $-3\Delta SV$, or

$$-3\Delta SV = \frac{3p \Delta V}{E} \left(\frac{1 - \mu}{2} \right) \frac{3b^3}{b^3 - a^3} \quad (6)$$

Another expression containing the pressure p will be found by considering the compressibility of the restraining particle. Reduction in volume of the particle caused by pressure p on it will be equal to the reduced space available to it within the larger body, or

$$\frac{3(1 - 2\mu_g)p \Delta V}{E_g} = 3S \Delta V - 4\pi a^2 \delta \quad r = a \quad (7)$$

where E_g and μ_g are the elastic constants of the particle and δ is given by Eq. (4).

Eliminating p between Eq. (6) and (7) and setting $b/a = \infty$ gives

$$-3\Delta SV = \alpha S \Delta V \quad (8)$$

where

$$\alpha = \frac{3(1 - \mu)}{1 + \mu + 2(1 - 2\mu_g) E/E_g} \quad (9)$$

Setting $b/a = \infty$ will introduce an error especially for particles close to the surface. However, it is believed that this error is not relatively as important as others entering this derivation.

Let volume of aggregate per unit volume of mix be g ; then the increase in g due to the addition of one particle of volume ΔV to the mixture will be

$$\Delta g = \frac{gV + \Delta V}{V + \Delta V} - g = (1 - g) \frac{\Delta V}{V + \Delta V} \quad (10)$$

From Eq. (8) and (10)

$$\frac{\Delta S}{S} = - \frac{\alpha \Delta g}{1 - g} \frac{V + \Delta V}{V} \quad (11)$$

or, in differential form,

$$\frac{dS}{S} = - \frac{\alpha' dg}{1 - g} \quad (12)$$

The factor α is probably a function of g since the elastic constants of the mixture, E and u , may depend on g . But if α may be considered to be independent of g , then Eq. (12) integrates to

$$S = S_0 (1 - g)^{\alpha'} \quad (13)$$

where S_0 is the shrinkage that would occur if no aggregate were present. For later use this equation may be written in the form (29)

$$\log \frac{S}{S_0} = \alpha' \log \frac{1}{1 - g} \quad (14)$$

Test. To test the validity of the formula, $1 \times 7/8 \times 11\frac{1}{4}$ inch prisms were prepared with various percentages of aggregate ranging from 0 per cent to about 70 per cent by volume. Three different types of aggregate (pulverized silica, standard Ottawa sand, and gradation of aggregates) would also be an appreciable factor. Two cements, a high-early-strength and a normal, and two water-cement ratios were used to determine in what way the effect of aggregate might be influenced by type of cement and water-cement ratio.

Later it was decided to investigate reversibility of volume change of these specimens. For this purpose specimens were alternately submerged in water and dried in air. Each drying was at 50 per cent relative humidity for

at least 22½ days and each period of wetting continued for about two years.

(29)

Table 13 gives the general outline of conditions covered in the study.

TABLE 13—GENERAL OUTLINE OF
CONDITIONS IN STUDY*

Cements used	Aggregates used	Percent aggregate by absolute volume†	W/C by weight
High-early- strength	Silica flour	0	0.5
Laboratory mix of four brands of Type I	Standard Ottawa	5	0.35
	Standard Ottawa sand	15	
	Graded Elgin sand	80	
		65	

*Specimens were sealed in steel molds $\frac{3}{4} \times 1 \times 1\frac{1}{4}$ in., that were stood on end for 2 hr during setting of mortar. Each mold was turned end-for-end every 5 min. Curing was for 7 days under water at 78 F. Drying was for 22½ days or longer at 50 percent relative humidity, 70 F and the wetting period was 84 days under water at 74 F. Two specimens were made of each combination, a total of 72.

†As will be noted later, there were slight deviations from these values.

Mixes containing up to 5 per cent aggregate were too wet and those with 50 per cent or more reversal of the position of the molds during setting tends to offset some effects of bleeding, but many of the wet mixes were blemished because the combined effects of bleeding, shrinkage in absolute volume, and periodic turning of the molds. Some dry mixes had a high percentage of air voids though in most cases percentage of air was kept low by vigorous tamping. The wide range in plastic properties of the mixes may account for some of the non-uniformities in results.

Shrinkage during drying and expansion during wetting for the specimens made with high-early strength cement are shown graphically in Fig. 1 and 2. Similar results were obtained with normal cement but are not shown. Final shrinkage indicated by each curve was estimated. These results are given in Table 14.

The quantities $\log S_0/S$ and $\log 1/(1 - g)$ were computed from Table 2 and plotted in Fig. 3. According to Eq. (14) the data should be represented by a straight line passing through the origin. The data for $W/C = 0.35$ are represented fairly well by such a straight line with a slope equal to 1.7. Reasonable assumption that would give this value is $\alpha = 0.2$,

$$M_g = 0.25, E/E_g = 0.21.$$

Data for $W/C = 0.50$ are not represented as well by a straight line. The line shown has a slope of 1.7. Points which lie farthest from the line are mixes that were stiff and when cast contained a considerable percentage of air voids. If these points are neglected, the arrangement is excellent.

On the basis of data obtained it is concluded that the derived formula gives a good representation of the effect of aggregate on ultimate shrinkage due to change in moisture.

The validity of the formula, the data gives the following indications:

1. First shrinkage is greater than any subsequent expansion or shrinkage resulting from moisture change.
2. At a given aggregate content the shrinkage is approximately proportional to water-cement ratio.
3. After first shrinkage, subsequent volume changes are approximately independent of water-cement ratio.

4. When shrinkage of specimens of the higher water-cement are plotted against the square root of period of drying, the shape of the curves for second shrinkage are approximately different from those for first shrinkage in that they have considerable curvature near the origin.

TABLE 14—FREE SHRINKAGE OF SPECIMENS OF VARIOUS PERCENTAGES OF AGGREGATE

Absolute volume of aggregate per mix volume	Shrinkage in millionths					
	First shrinkage			Second shrinkage		
	Silica	Ottawa sand	Elgin sand	Silica	Ottawa sand	Elgin sand
W/C = 0.50						
0	5870	5870	5870	2180	2180	2180
0.05	4000	5450	5350	1720	2100	2100
0.15	3600	4500	3720	1530	1600	1500
0.30	2200	2850	2700	950	1100	1100
0.50	2000	1700	1650	740	670	640
0.67	—	—	890	—	—	410
W/C = 0.35						
0	3700	3700	3700	2050	2050	2050
0.06	3200	3450	3380	1700	1750	—
0.18	2410	2720	2600	1300	1380	1430
0.34	—	1800	1810	—	1000	1000
0.53	—	940	1080	—	540	620
0.62	—	—	900	—	—	300

Application of the hypothesis to test results. (30) The first shrinkage is greater than any subsequent expansion or shrinkage because the arrangement of gel particles and groups of gel particles is changed during first shrinkage. At a given aggregate content the extend of first shrinkage should increase with increase in water-cement ratio. The original spacing of cement grains depends on the water-cement ratio and therefore the average spacing of the gel particles in their first arrangement subsequent to volume change are

approximately independent of water-cement ratio because after one having been dried the spacing between adjacent gel particles should be more a function of humidity and of the corresponding degree of drying than original spacing. The gel from mixes of higher water-cement ratio will have a more open structure between agglomerations of particles but not necessarily any greater capacity for changes in volume.

Volume change takes place in concrete for causes other than stress. Temperature effects the volume of concrete its coefficient of expansion being about 0.000,005, 5 per degree Fahrenheit. The volume change due to permanent shrinkage is an important factor. Shrinkage is greatest during the active hardening process and probably continuous at greatly diminished rate of the life of the concrete for concrete structures exposed to the weather (about 70 per cent humidity) shrinkage is of the order of 0.000,5. Shrinkage is much greater for structures in arid surroundings and is negligible for structures continually wet. (31)

When the shrinkage of the bars become asymptotic with respect to time, they were placed in water and the expansion was measured. The findings of this study were,

1. Shrinkages of mortars increase with increase amounts of shale and sandstone in the natural sand.
2. Shrinkages of the oven-dried bars bear a linear relationship to the shrinkage of those dried by means of the calcium chloride dessicant, although the first series shrink less than those dried at 21C.
3. As can be seen from Figs. 3 and 4 there is a relationship between the first shrinkage and the expansion due to the first immersion in water.

The general crack, patterns, which was unlike that associated with foundation movements, structural failure, or expansion and contraction normally

attributed to drying, or thermal effects, could only be explained on the basis of excessive shrinkage and expansion of the concretes. This dimensional change behavior was found to be associated with the use of a specific type of aggregate.

1. Excessive shrinkage - over-all shrinkage which may be unaccompanied by cracking is often in the opening of contraction joints in structures.

2. Deflection of reinforced members - In the absence of an externally applied load, deflection in a beam results if the concrete in the beam tends to shrink, but is asymmetrically restrained by reinforcement. The greater the shrinkage the larger the deflection due to this phenomenon are visible in case of bridges.

3. Cracking of concrete coincident with the reinforcing steel is noted in most of the structures affected by excessive shrinkage.

The size and position of the steel, with respect to the surface from which evaporation of water takes place, appears to govern this type of each. In thin members, where steel is closed to the surface and drying is rapid, cracking is most likely to occur. Once cracking coincident with steel take place, corrosion will resultant expansion leading to spalling of the concrete.

4. Grazing and map cracking - Crazing is associated with stresses step up by differential shrinkage and expansion between the surface and internal layers of concretes and mortars.

Lightweight Aggregate

Lightweight aggregate may be classified with regards to sources as either natural or from artificial production. They may be specially processed by expanding, calcining, or sintering suitable products, natural materials

diatomaceous shale, pumice, tuff, obsidian, perlite vermiculite, etc. (10, 1, 3)

The absorption of ordinary burned clay aggregates is considerably more than for those which are hard-burned and have a denser shell. As all lightweight aggregates are more porous and absorptive than ordinary aggregates, it is usually necessary to wet them before they are used. (3)

In placing lightweight concrete especial care must be taken to prevent segregation of the coarser particles from the mortar. Because of their lightness, they tend to rise toward the surface and cause segregation more readily than for ordinary aggregates, which tend to move downward in a wet mix. For this reason, highly fluid mixes should not be employed with them.

In general, the lower the weight, the lower the strength of a given mix. The compressive strengths of most lightweight concretes are somewhat lower than for ordinary concretes having the same water-cement ratio and subjected to the same curing conditions. Also, the modulus of elasticity of lightweight structural concrete is lower, probably because of the greater compressibility of the aggregates. The modulus for such concretes ranges from about 1,000,000 to 3,000,000 psi at 28 days. The shrinkage of lightweight concrete is generally greater than for normal concrete of the same mix and consistency.

As the physical properties and durability of various lightweight concretes, and their suitability for particular uses, may vary with the different types of lightweight aggregates. (1)

Manufacture. In order to produce an expanded aggregate two conditions must occur simultaneously during the burning process; the raw material must be heated to the point of fusion, and gases must be evolved within the mass at the same time. If these do not occur simultaneously, the gases will not

effect the desired expansion.

In the investigation of clays and shale in Ohio, found that carbon dioxide was the principal gas causing expansion.

The CO_2 was generally produced by decomposition of calcite, although other carbonate materials such as ankerite and dolomite were the sources of the gas in a few samples. Since calcite decomposes at about 1630 F, it is desirable that a large portion of the raw material contain a clay mineral which will fuse near this temperature. Of the more common clay minerals illite fuses at 1830 to 2370 F and Kaolinite 3000 to 3230 F. A high percentage of illite occurred in all samples that produced satisfactory expansion.

Pyrites, hematite, and organic materials such as coal, coke and oil are also potential gas producing agents and have been used as additives to improve the bloating characteristics of certain clay and shales. The gases evolved from coal or coke may be retained in the fused material to cause bloating or with some materials, the organic material is merely decomposed to leave a void without appreciable expansion of the aggregate particle.

Blast-furnace slag is expanded by treating molten slag with controlled quantity of water to produce a strong, highly vesicular aggregate. This may be accomplished by either the pit "or machine" process and the products of each process are finding increased use in structural concrete for floors and for fire protection of steel beams and columns. (32)

Structural Properties. Concrete with 28 days compressive strengths 3000 and 4500 psi was made with each of the aggregates other structural properties, such as modulus of elasticity, flexural strength, bond to reinforcing steel, creep and shrinkage were comprised on a basis of equal compressive strengths.

In order to obtain a certain compressive strength of concrete the cement content was adjusted as required for each aggregate. About five per cent purposely entrained air was incorporated in each mix, slump was maintained between two and three inches. Type I portland cement was used throughout. The cement content and unit weight of the unhardened concrete containing each of the aggregates are shown in Table 15. The cement content required to produce concrete with a 28 day compressive strength of 3000 psi varied from 4.4 to 6.7 sacks for the lightweight aggregates compared with 3.9 sacks required for the sand-and-gravel concrete. In the 4500 psi series, cement gates compared to 4.8 sacks for the heavier concrete. Unit weight various lightweight concrete in both series varied from 90 to 110 lb per cu ft compared at about 145 lb for the regular concrete.

TABLE 15—CEMENT CONTENT, UNIT WEIGHT AND AIR CONTENT
(Normal and Accelerated Curing)

Agg. No.	C-Series			H-Series			S-Series		
	Cement Content sk/cu yd	Unit Weight lb/cu ft (Wet)	Total Air %	Cement Content sk/cu yd	Unit Weight lb/cu ft (Wet)	Total Air %	Cement Content sk/cu yd	Unit Weight lb/cu ft (Wet)	Total Air %
3	6.90	97.3	6.5	7.24	101.4	4.5	7.33	101.8	4.2
4	5.62	104.1	5.5	6.06	107.3	4.0	6.08	107.7	4.7
5	7.94	105.4	7.0	8.37	109.1	5.0	8.46	109.1	4.6
6	9.32	115.4	6.5	9.42	115.5	5.5	9.66	118.2	4.0
7	8.32	113.6	5.5	8.57	116.4	3.5	8.67	117.3	4.0
8	5.00	150.4	3.3	5.10	152.7	3.3	5.10	152.3	3.0
Av	7.18			7.46			7.53		

The modulus of elasticity of lightweight concrete is generally about half that of the heavier concrete of the same strength for a given maximum size aggregate. The natural sand is used as complete replacement of the fines, to raise the modulus of elasticity. The natural sand may sometimes

also improve the strength and workability, but will add as much as 20 lb to the unit weight.

Under moist curing conditions flexural strength of the lightweight concrete was approximately equal to that of sand-and-gravel concrete of the same compressive strength.

Under drying conditions the lightweight concretes suffered a rather severe loss of flexural strength for several months but recovered as moisture differences between the interior and exterior of the concrete diminished at later ages.

Strength. Two factors enter into the strength of the lightweight concrete the strength of the aggregate and the strength of the hardened cement-water paste. Among the various types of lightweight aggregate there are large differences in strength and toughness, and all but the strongest lightweight aggregates are highly to be weaker than hardened cement-water pastes within the usual range of cement contents.

As a general rule, the strength of the lightweight concrete will be less than that of a concrete equal cement but containing aggregate of normal weight. Also, with a given cement content, the lower the strength of the lightweight aggregate the lower will be the strength of lightweight concrete.

In general, for a given type of lightweight aggregate, the strength of the aggregate (and consequently the concrete) varies roughly with the unit weight of the aggregate.

The strength also varies inversely with absorption ASTM Specification C330 required that structure concrete be produced that will satisfy one or more of the compressive strength requirements in Table 16 without exceeding the corresponding maximum absorption and unit weight values.

TABLE 16—SPECIFIED RELATIONSHIP
OF THE PROPERTIES OF STRUCTURAL
LIGHTWEIGHT CONCRETE.

28-Day Compressive Strength, min, psi	Absorption, max, per cent by volume	Unit Weight, max, lb per cu ft
4000	15	115
3000	18	110
2000	21	105

Although various lightweight structural concretes exhibit large differences in resistance to the destructive action of freezing and thawing, it appears that those containing aggregate of low absorption and having a compressive strength above 2000 psi can be classed as satisfactory. No disruption from alkali aggregate reaction has been observed in lightweight concrete.

Popout materials in lightweight aggregate are prohibited by the current ASTM Specification C330 and C331. The iron compounds, if staining is excessive, a chemical analysis is made, and such an aggregate that contains more than a specified amount of ferric oxide is rejected. (1)

Shrinkage. Investigations have shown that the shrinkage upon drying of lightweight concrete having the same cement content. One factor tending to cause high shrinkage is the use of excessively wet mixes influencing shrinkage are the rigidity of the aggregate (restraining the shrinkage of the paste) and the size of its pores or capillaries. High shrinkage alone is not necessarily indicative of any pronounced tendency toward cracking. Since resistance to cracking also involves tensile strength, modulus of elasticity and creeping (plastic flow) of the concrete.

Natural and manufactured lightweight aggregates are generally free from corrosive compounds and may be used safely in contact with steel. Cinder concrete has been questioned with respect to the effect of sulfur and perhaps of other compounds, but large quantities of properly made cinder concrete not exposed to moist conditions have been in service for many years without ill effects on the metal with which it is in contact. (1)

Bond. Strength of the lightweight of concrete to reinforcing steel is very good. With the modern, highly deformed reinforcing steel, bond strength becomes a function of the concrete, so that at equal compressive strengths comparable bond should be expected. Settlement and bleeding of the concrete allow air and water to accumulate beneath the top-position bars, thus reducing the bonded area.

Creep. Creep is the long-time deformation of the concrete under sustained load, and creep tests required a long time, generally about 18 months, in order to arrive at reliable creep coefficients. A creep coefficient is a value indicating the ultimate creep per psi of load. Larger creep coefficients indicate greater deflection of beams; greater transfer of load from concrete to steel in columns, and greater steel-stress loss in prestressed members. The creep coefficients of some lightweight concretes compare very favorably with those for sand-and-gravel concrete. However, in the initial investigations creep coefficients of some lightweight concretes were as much as 60 per cent greater than those of regular concrete. Drying shrinkage of some lightweight concretes was approximately equal to that of sand and gravel concrete; with other, shrinkage was greater by as much as 38 per cent. (32)

SUMMARY

1. The unit weights of the various lightweight aggregate concretes in the lower strength series ranged from 90 to 110 lb per cu ft compared with 146 for sand and gravel concrete. The expanded shale aggregates from rotary kilns produce the lower-weight concretes. The expanded slag and sintered shale produced the heavier lightweight concretes.

2. The various lightweight aggregates required a wide range of cement content to produce similar strengths. The 3000 psi concretes required between 4.4 and 7.2 bags per cu yd, and the 4500 psi concretes required between 6.0 and 8.9 bags per cu yd. Strengths in excess of 8000 psi were obtained with one of the lightweight aggregates in a 10 bag mix. The strength gain of the lightweight concretes under continuous moist curing and under drying at 50 per cent relative humidity was similar to that of sand-and-gravel concrete.

3. The modulus of elasticity of the lightweight aggregate concretes in 3000 and 4500 psi series varied from 53 to 82 per cent of the modulus of sand and gravel concrete, based on values obtained from moist-cured cylinders at 28 days. At later ages there was a greater difference between the moduli of the lightweight and normal weight concretes.

4. The flexural strengths of the lightweight and sand-and-gravel concretes were approximately equal at early ages but after 28 days the sand-and-gravel concrete showed greater strength gain with continuous moist curing than did the lightweight concrete. (33)

5. Bond strengths of some of the lightweight concretes were approximately equal to those of the sand-and-gravel concretes. Lowest bond strengths were obtained with top-position bars in concrete which showed pronounced bleeding.

In the 3000 and 4500 psi series all specimens, with a single exception, failed either by yielding of steel or at bond stresses in excess of 900 psi when the bar was in a vertical position. In the high-strength series, all specimens failed at bond stresses in excess of 1430 psi.

6. At early ages the creep of some of the lightweight concretes was less than of the sand-and-gravel concrete. In the lower-strength series two of these lightweight concretes had approximately the same creep at the sand-and-gravel concrete at age one year. However, the computed ultimate creep of the lightweight concretes, with a single exception, is greater than that of the sand-and-gravel concrete, as indicated by the creep coefficients.

7. In the lower strength series at age 6 months the drying shrinkage of the lightweight stored at 50 per cent relative humidity was between 95 and 138 per cent of that of the sand-and-gravel concrete. The predicates a ultimate drying shrinkage of the lightweight concretes for 50 per cent relative humidity is between 106 and 138 per cent of that for sand-and-gravel concrete as indicated by the average coefficient. In the high-strength series the drying shrinkage of the sand-and-gravel concrete was intermediate between the two lightweight concretes.

8. There was no evidence of alkali-aggregate reaction with any of these aggregates when tested with a cement having an alkali concrete of 0.63 per cent.

9. Within the group of lightweight aggregates studied rather wide variations were obtained in the structural properties of the concretes. This was true of lightweight aggregates that were similar in appearance and produced by similar processes. It is important, therefore, that individual producers of lightweight aggregates for structural concrete purposes conduct investigations that will provide reliable design data on performance characteristics. (33)

CONCLUSIONS

This paper has discussed the problems of the effects of the aggregate on the quality of concrete with respect to its workability, durability, strength, shrinkage and lightweight aggregate.

To insure that concrete will be made of high quality aggregate, both good specifications and adequate inspection and control are essential; one alone can do only a partially successful job. Specification writers should be familiar with the effects of various aggregate properties and conditions on the quality of concrete. Inspectors should be able to differentiate between good and inferior aggregates, and should insist upon proper handling of materials.

Since a young inspector on the job today may be the specification writer of tomorrow, it is to his advantage, as well as to his employer's, to keep accurate records of aggregates, concrete mixes, placement data and service performance on all his jobs.

In determining relative economy of various aggregates, cost per ton is not the only factor to be considered. Aggregates which cause deterioration will almost invariably prove to be far more expensive than those of good quality, regardless of first cost. Another cost factor which results from variations in aggregates is the increase or decrease in cement requirement. The cost of washing to eliminate silt, clay or organic impurities can generally be justified unless a clean aggregate is available nearby. Sacrificing quality in order to save a few cents per ton is costly in the long run.

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EFFECT OF AGGREGATE ON THE QUALITY OF CONCRETE

by

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The purpose of this report is to discuss the effect of aggregate on the quality of concrete. Aggregate either fine or coarse is inert filler material added to cement paste to increase its bulk. The principal qualifications of aggregate for concrete are that they be clean, hard, tough, strong, durable and of the proper gradation.

There are too many variables which affect workability for it to be the maximum size of the aggregate, the capacity of the aggregate to absorb water, shape and surface characteristic of aggregate particles, grading of aggregate, plasticity of the paste itself, and relative quality of paste and aggregate.

In order that concrete be durable, in so far as the influence of the aggregate is concerned, it is important that the aggregate be resistant to weathering action, that no unfavorable reaction take place between the aggregate minerals and components of the cement, and (3) that the aggregate contain no impurities which affect the strength and soundness of the cement.

Temperature changes alone have been found responsible for unsatisfactory service records of some concretes, particularly when the changes are rapid, it tends to set up large differential strains between the surface and interior of the mass. Certain aggregates having an especially low coefficient of thermal expansion have given poor service at low temperatures, causing high tensile stresses in the matrix of cement paste. Thermal concrete temperature is dependent on the initial concrete temperature, the heat of hydration of the cement, the outside temperature, the rate of construction, and thermal changes in mass concrete are kept as low as possible by the use of low-heat portland cements and also by artificial refrigeration.

When water freezes, it expands, this expansion can cause a high internal pressure sufficient to disrupt even the strongest concrete. For a concrete to

be resistant to frost, it should have a low water content, absorption, low permeability and should be strong. If the concrete contains small entrained air bubbles, then the damage will be less. The size or thickness of the body also has effect on freezing. The rate of freezing and critical size of aggregate have also effect on hydraulic pressure. The aggregates with poorest durability had voids ratio of the small pores several times as great as did some of the most durable materials.

Air entrainment increases frost resistance of concrete and improves the workability and produces less segregation and bleeding, and gives a more homogeneous mixture.

The cause of expansion and disruption of concrete by the reaction of cement with aggregate has in the formation of an alkali silica gel which swells and so produces an expansive pressure.

The alkali reactive with carbonate rock was found that the rates of both expansion and dedolomization are functions of the calcite dolomite ratio and texture of the rock. Maximum reaction occurs when calcite and dolomite are present in approximately equal amounts and when both are extremely fine grained.

The crushing of average rock aggregate is higher than the strength of the concrete made with them usually the aggregates bond controls the strength. There are too many variables which affect the strength for it to be type of the mineral aggregate, shape and surface characteristics, aggregate-cement ratio, and the maximum size of the aggregate.

Recently, it was found that for a given water-cement ratio, strength becomes less as the maximum size of coarse aggregate is increased. Maximum strength for both flexural and compressive strength were secured with coarse aggregate of about $3/4$ inch.

Creep is affected by the type of aggregate. It is reduced by using a large aggregate and insuring a small voids and also by using flint gravel or low absorption limestone.

The ability of normal aggregate to restrain the shrinkage of cement paste depends upon extensibility of the paste, degree of cracking of the paste, compressibility of the aggregate, and volume change of aggregate due to drying.

Lightweight aggregate may be classified with regards to sources as either natural or artificial production. The unit weight of various lightweight aggregate concrete is about two-thirds of ordinary aggregate concrete. The strength of lightweight aggregate concrete is proportional with its density.

In general, the problem of the quality of concrete is selecting and proportioning of the different sizes of aggregate particles, quality of mineral aggregate, shape and surface roughness of the aggregate, water-cement ratio of the paste, and the quality of the cement.